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RELIABILITY IMPACT OF MICROGRID AND USE IN (MV) DISTRIBUTION ELECTRICAL NETWORK

Master of Science thesis

Examiner: Professor Sami Repo
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ABSTRACT

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Security and adequacy are two prominent issues among other issues in electrical power system at present time. Heterogeneous geographic terrain needed diverse types of power distribution network carrying different level of network reliability. Power system disturbances are responsible for power interruption to the network hence interrupted power supply causes poor network reliability. It has been acknowledged that microgrid is one of the possible ways ahead to enhance grid reliability. This thesis complies research results of the reliability impact of the microgrid in medium voltage grid. It also shows the reliability impact of using Battery Energy storage (BESS) as microgrid backup source in gird. Microgrid position, microgrid source capacity (BESS size), network fault rate and network fault duration have been also considered for deep reliability analysis a grid.

Finnish power distribution network data has been used in this research to assess the reliability impact of the microgrid. Comparative research study over the network during grid-connected mode and microgrid mode have been studied in this research. In all cases simulation results prove that microgrid has significant impact on reliability of the network. This research also illustrates that microgrid position influences overall grid reliability during microgrid operation. This research also deals with the impact of microgrid number and microgrid source capacity over the grid reliability. Increased microgrid number in the network improve overall network reliability. On the other hand, grid reliability increases with respect to the increased microgrid source capacity too.

PREFACE

It is a wonderful opportunity to be graduated as master's degree graduate from Tampere University of Technology. Master's thesis is one of the vital parts of master's Degree program. This Master's thesis report has been completed as the requirement of master's degree under supervision of prof. Sami Repo in electrical department, with the major in Smart Grid.

Firstly, I would like to show my gratitude to the Almighty God. Then I like to give thanks to my supervisor Professor Sami Repo specially for his initial guidance about selecting the thesis topic at the same time for clear instruction to reach the thesis goal.

I would also like to show my enormous thanks to Antti Supponen for elucidating practical work. He assists me a lot to overcome my novice period as well as guiding in thesis writing. At last I am grateful to my family members Md. Saidur Rahman, Mst. Shakura Begum, Md. Sumon Shahriar, Wahida Rahman, Sharmin Sultana as well as to other friends including Zahangir Khan, Shahriar Parvez and Mohammad Akter Hossain.

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M. Sabbir Rahman

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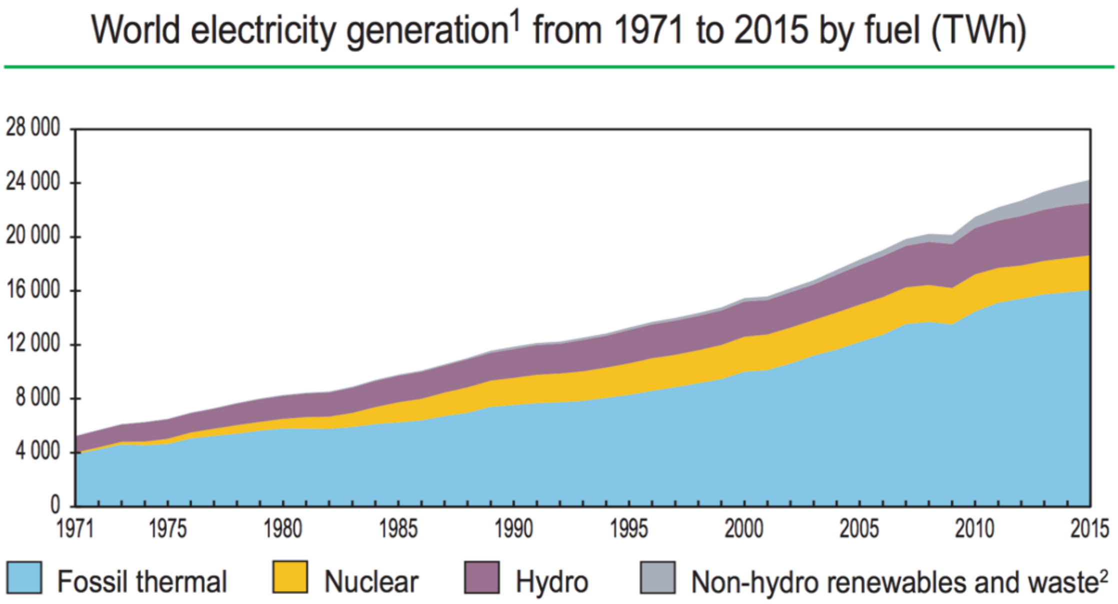
LIST OF SYMBOLS AND ABBREVIATIONS

DG	Distributed Generation
BESS	Battery Energy Storage System
ES	Energy Storage
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
MG	Micro Grid
DER	Distributed Energy Resources
PV	Photo Voltaic
WT	Wind Turbine
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
CAIDI	Customer Average Interruption Duration Index
CTAIDI	Customer Interruption Total Average Duration Index
CAIFI	Customer Average Interruption Frequency Index
ASAI	Average Service Availability Index
CEMI	Customer Experiencing Multiple interruption
CML	Customer Minutes Loss
TIEPI	Equivalent Interruption Duration Index
MAIFI	Momentary Average Interruption Frequency Index
MAIEFI	Momentary Average Interruption Event Frequency Index
ENS	Energy Not Supplied
AENS	Average Energy Not Supplied
ASIDI	Average Customer Curtailment Index
ASIFI	Average System Average Interruption Frequency Index
ASAIDI	Average System Average Interruption Duration Index
AIT	Average Interruption Time
AIF	Average Interruption Frequency
AIT	Average Interruption Duration
FRT	Fault Ride Through

1. INTRODUCTION

The modern world is highly dependent on electrical energy directly or indirectly for home and industrial purposes due to its usability as well as flexibility with maximum efficiency compared to other sources of energy for example, oil, natural gas, coal and nuclear resources. According to the world energy statics report, around 90% of the total electrical energy produced from non-renewable resources and rest of comes from renewable energy



resources.

Figure 1: Electricity production from different resources [1]

Electric power plants and consumer zones are situated at a certain distance from each other due to environmental or economic issues. Electricity could be transmitted through an overhead or underground transmission line for thousands kilometer from power plant to the end users via different power station, sub-station sequentially.

Long distance transmission line could be run through different geological region i.e. forest, lake or mountain which have the great chance of network fault due to various natural calamities i.e. storms, snowfall earthquake. Electrical network faults caused interruption in power supply hence to accelerate economic loss as well as decrease network reliability. So, minimization of interrupted customer number could be one of the main methods to increase network reliability[2]

Ecofriendly thinking, technological advancement and economic advantages have insisted very considerably the penetration of renewable resources and make microgrid (MG) concept as widespread research field to enhance the power grid reliability[3]

Installing energy storage system with renewable energy resources will make the grid more reliable and secure power supply. There are multiple types of energy storage systems based on energy density, permissible life cycle, charging-discharging time, cycle efficiency optimal storage energy is available. Energy storage system could supply instant energy to the grid and discharging with low power losses which improve grid performance[4]. Battery energy storage system (BESS) could be used as micro source in microgrid (MG) due effective system frequency and voltage support.

In this research multiple grid operation modes have been studied well to understand the reliability impact of microgrid on MV distribution electrical network. Auxiliary power supply mode, fault ride through (FRT) condition, nominal microgrid condition and maximum microgrid power supply mode have been considered in this research to analysis reliability impact over the grid. More detail explanations about these grid condition will be found in third chapter.

1.1 Research objectives

The main objectives of the thesis are as follows: -

a. Developing methodology to analyze the reliability impacts of microgrid/BESS on distribution grid in some certain conditions: -
    - SAIDI determination in auxiliary power supply or multiple backup power supply condition.
    - SAIFI and SAIDI determination during fault ride through (FRT) condition.
    - SAIDI determination in nominal microgrid condition
    - SAIDI determination in maximum microgrid power supply condition.

b. Analyze a real-life case study of active microgrid/BESS and extrapolate how microgrid/BESS effects on grid reliability. Comparative result analysis has been done based on some factors which are given bellow: -
    - Impact of BESS/BESSs capacity in grid performance.
    - Impact of BESS/BESSs number on grid reliability.
    - Impact of BESS/BESSs location on grid reliability.
    - Sensitivity analysis in microgrid condition.

1.2 Scope

Analysis of reliability impact over a distribution network is a broad research field. As master's thesis, it is not feasible to cover the all possible research area for certain constraints. Protection devices, reclosing devices, sectionalizing switches, distribution automation, faster crew response, fewer equipment failure and system configuration are the possible existing ways to enhance the overall grid reliability in traditional method. High penetration of renewable energy and development of power electronics make easy to introduce microgrid technologies in the grid to secure available backup power for interrupted loads during fault to improve grid-reliability. This research paper focuses on narrow area specially how to develop the reliability calculation tools, how reliability indices (SAIFI and SAIDI) change while the grid switches normal grid-mode to islanding-mode. Furthermore, the impact of auxiliary power supply, BESS capacity, BESS location and BESS number over reliability indices have been documented in this research.

Firstly, it has been assumed that the grid is well equipped with necessary grid protection system. Grid Protection system analysis has not taken in consideration during grid reliability calculation and islanding operation. Secondly, nominal microgrid and maximum microgrid power supply operation has been implemented based on assumptions; each micro source (BESS) in a load point can supply power to the connected load at the same time supports other load points with required quality power if possible.

1.3 Thesis outline

This thesis paper includes four main chapters, each chapter holding multiple subchapters. First chapter focuses on literature of electrical power system, microgrid, microgrid topology, microgrid protection. Third chapter illustrates the way of developing methodologies for system reliability calculation during different grid operation mode. Fourth chapter discussed about simulation results and analysis. The whole thesis structure has been visually presented in Figure 2. It goes to discuss the reliability impact of microgrid in the distribution power system.

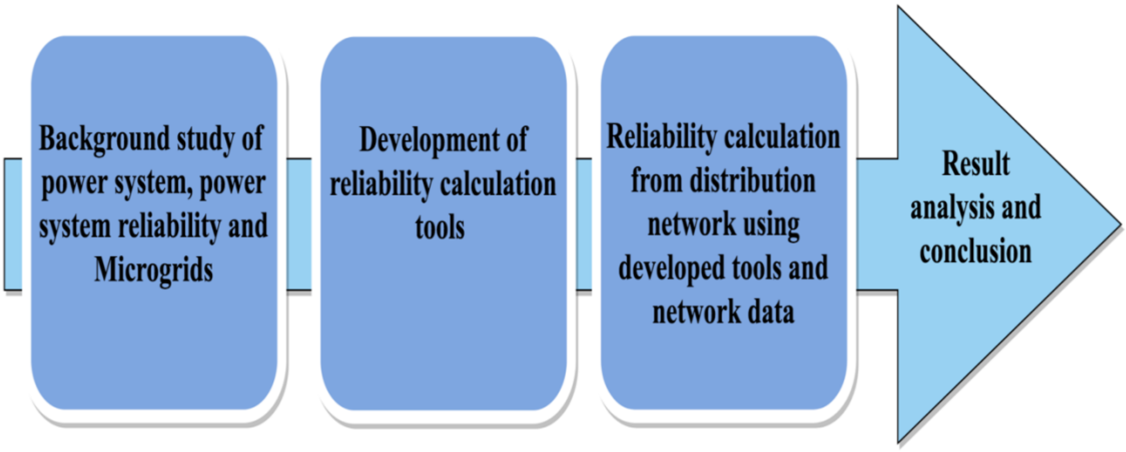


Figure 2: Structure of the conducted research

2. POWER SYSTEM RELIABILITY AND MICROGRID

2.1 Electrical power system

The electrical power system is the large at the same time complex system which is one of the modern creation of humankind in the present era. The distribution system is the part of an electrical power system that delivers electrical energy to the end user from generation point via the transmission system. Electrical power system consists of many components, structure, system, subsystem, equipment which are connected in a complex form to facilitate electric power to the homes, industries and other emergency services like a hospital. Figure 3 shows a schematic diagram of an electrical power system. This thesis deals with medium voltage radial Finnish distribution network which is under primary distribution zone according to the Figure 3. Electrical power system confederate's modern society in such way that it is unimaginable to think without electricity. This accentuates the importance of the reliability of electrical power system.

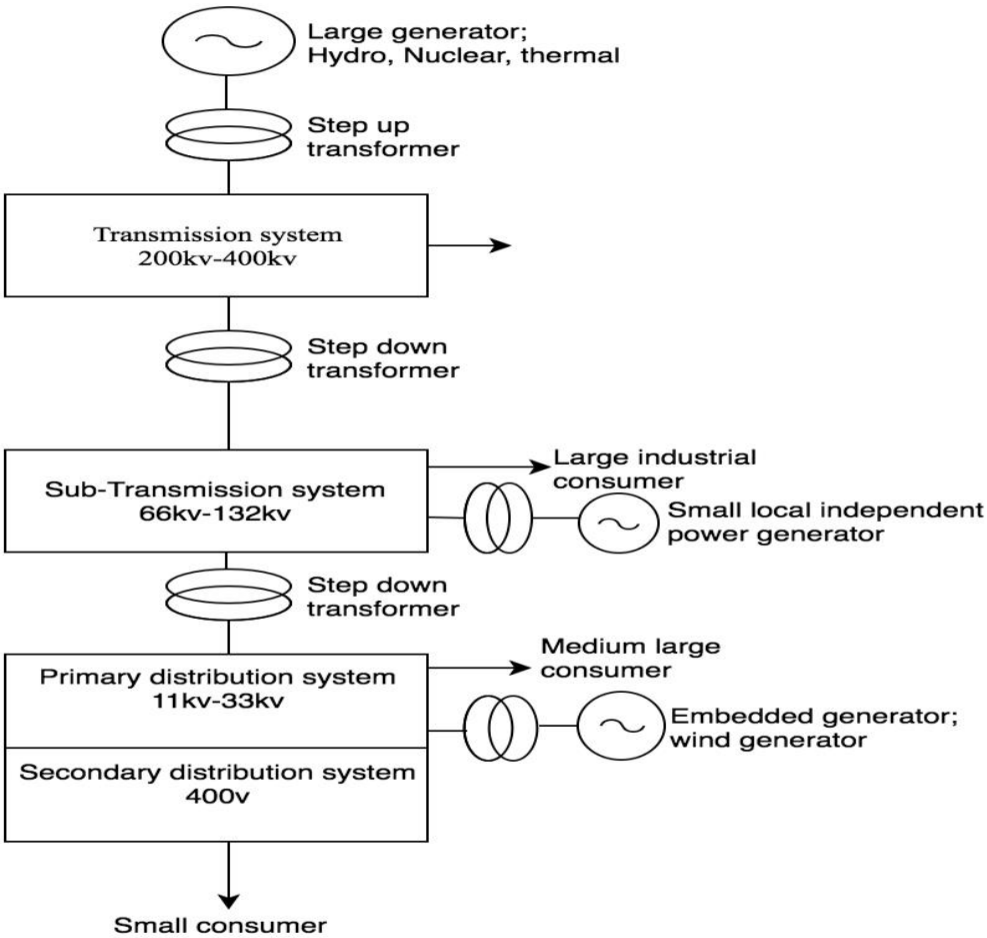


Figure 3:Schematic diagram of power supply system[5]

2.1.1 Major disturbances of power system

Diverse types of power system disturbance are responsible for power outage in the electrical system. Interruption of power supply decreases system efficiency or reliability. Some examples of power system disturbances are given bellow-

Shunt Fault: Shunt fault is treated as one of the major disturbances in power system. Three phase-to-ground, three phase-to-phase and two-phase to the ground fault are the examples of the different type of shunt faults. The most common fault is the phase-to-ground fault caused by insulation fail, lightning strokes, switching surge or mechanical failure due to high wind force or snow or ice. A slow fault-creation mechanism may lead to arc-over or flashover at the peak voltage while insulation fails. The grounded transmission line, fallen tree over the heavily loaded transmission line causes failure of insulation hence flashover occurred.

Generator system disturbance: The loss of excitation in a generator unit due to human error influences surrounding system voltage hence causes miss-synchronization of the generator. Miss-synchronization of a unit resulting power plant trip at the same unit start to oscillate with the power system and creates a high asymmetrical current. Current Transformers (CTs) connected with the differential relay are stressed by high asymmetrical current flow and the relay start to run unevenly resulting in a false trip of the relay.

Cable transmission feeder system disturbance: At high-pressure fluid-filled cable not capable to support insulation, hence asymmetrical fault occurs. Fault current generated force explodes the pothead of the cable and damages other equipment's.

Breaker failure protection system disturbance: Unit breaker could misbehave mechanically during an attempt to synchronize with the system and resulting in an out-of-step position with three times oscillation with the system. [6]

2.1.2 Power system protection

The increased demand for electrical power in both developed and developing countries, need an acceptable level of reliability, quality with good safety at a cost-effective price. Shortest outage duration and continuous power supply of a network could be carried out through good network protection systems which are the prominent issue to support good network reliability. Permanent fault causes long outage duration to the customer and may also damage electrical equipment in the distribution network. A properly coordinated network protection system has some prime requirements.

- **Selectivity:** Ability to detect the faulty part of the network and isolate least part of the network with maintaining supply in rest of the portion of the network.
- **Speed:** Ability to execute protection in minimum time to prevent the damage of equipment.
- **Sensitivity:** Capable to sense minimum fault current along with system abnormalities and perform protection to the network as faster as possible.
- **Economic consideration:** The complexity and cost of the protection system could be selected based on two factors; the cost of faults and the desire level of supply security. Higher fault cost desire complex and expensive protection system[7-9]

2.1.3 Power system reliability

A system consists of subsystems and the subsystem could be divided into multiple types of components or more precisely thousands of equipment which are the factors of the reliability of a system. The human action error and inability of a part of a system or subsystem to perform required action has a contribution to system reliability. According to the general definition, the reliability of a system is the probability P of performing a required function under certain condition. So, reliability $R(t)$ could be a function of required events (E) for certain condition.

$R(t) = P\big[E\ did\ not\ fail\ in\ time\ interval[0,t]\big]$……………………………….. (1)

Again, reliability $R(t)$ is the probability of continuous random variable which value is larger than *t,* could be mathematically defined with respect to the probability density $f(t)$

$R(t) = \int_t^{\infty} f(t)dt$…………………………………………………..….. (2)

While the random variable is discrete,

$R(t_i) = \sum_{i=1}^{i=k} f(t_i)$………………………………………………………………. (3)

In power system, reliability is divided into two terms; adequacy and security which refers the availability of enough generation for existing consumer demand and the capability of the electric power system to respond in any transient or disturbance period respectively [10, 11]

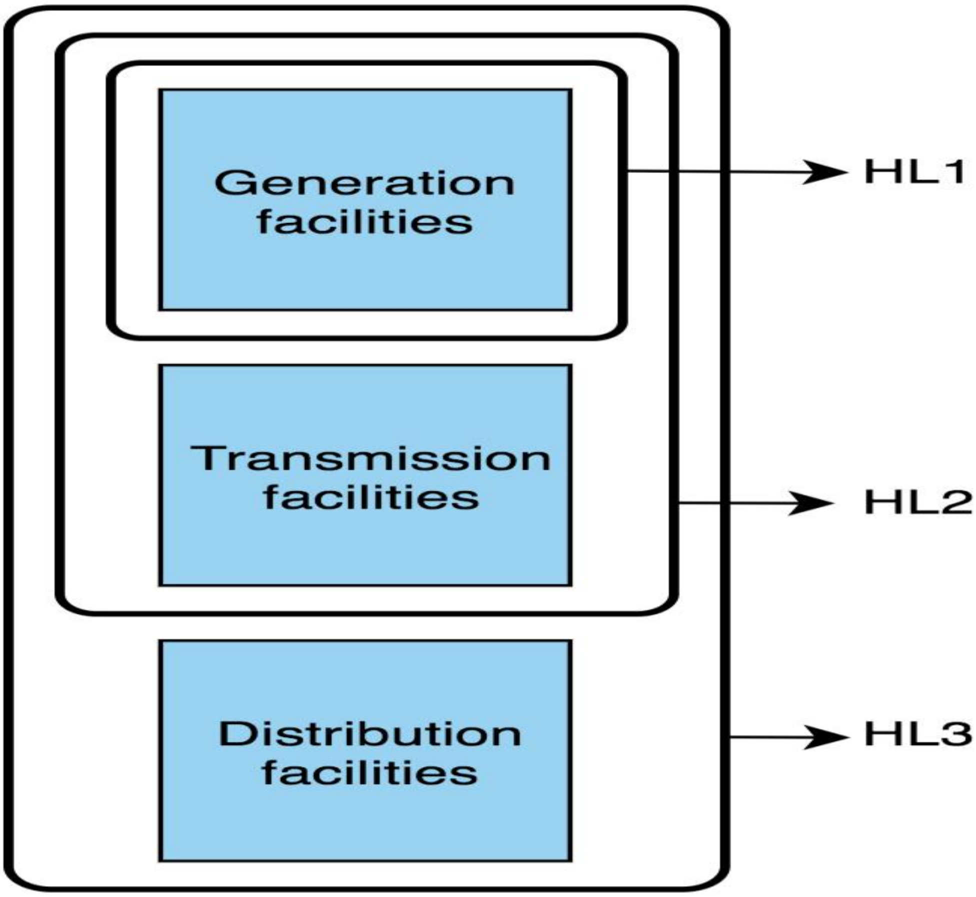


Figure 4: Hierarchal level[11]

Adequacy assessment technique of a complete power system could be divided into main three segments; generation facilities, transmission facilities and distribution facilities. Each segment is called functional zones and three functional zones introduce hierarchal level concept for adequacy assessment. Hierarchal level 1 (HL1) deals with only generation facilities. On the other hand, generation facilities and transmission facilities both are considered in Hierarchal level 2 (HL2). Lastly, Hierarchal level 3 (HL3) considers all three segments of the complete power system. Hierarchal level shown in Figure 4 [11]

2.1.4 Reliability indices

Major dependency on electrical power, utilities needed correct information about electrical network performance for economic benefit as well as to meet the customer expectation. System reliability deals with existing interruption or momentary interruption while, power quality deals with voltage fluctuation, abnormal waveforms, and harmonics behavior. A system performance is evaluated or understood by the reliability indices value. System Average Interruption Frequency Index (SAIFI), the System Average Interruption Duration Index (SAIDI) are most common two reliability indices are used in power system network. Fault repair time of a compact distribution power system helps to optimize power system reliability[12] .These reliability indices also indicate the system ability in any hazardous condition such as cable or equipment's failures, system utilities and maintenance performances[13] . Some basic definitions are required to determine Power system reliability indices which are given below: -

- **Interruption:** The unavailability of total electrical power on one or more normally energized conductor to the customer connected part of the distribution system is called interruption.
- **Interruption duration:** The period of restoration of power to the affected customer is called interruption duration.
- **Momentary interruption:** A fleeting period loss of power delivery to the customer due to interruption device operation (opening or closing) called momentary interruption.
- **Outage:** The loss of capability of the system part to supply power to the load. Transmission and distribution outage are not applicable for generation outage which may or may not responsible for interruption service to the customer.

A list of sustained interruption-based indices for an electrical power system is shown Table 1.SAIFI and SAIDI both indices are used to analysis the network reliability in this research.

Table 1: Sustained interruption-based indices[14]

Indices	Full Name	Description
SAIFI	System Average Interruption Frequency Index	SAIFI denotes how often the average customer experiences the sustained interruption over a predefined of time.
SAIDI	System Average Interruption Duration Index	SAIDI indicates the total interruption duration of the average customer during the predefined period.
CAIDI	Customer Average Interruption Duration Index	The average time is required for restoration the service is called CAIDI.

CTAIDI	Customer Interruption Total Average Duration Index	CTAIDI is the hybrid of CAIDI which is calculated an analogous way of CAIDI except multiple interruption is counted only once.
CAIFI	Customer Average Interruption Frequency Index	CAIFI indicates the average frequency of sustained interruption for interrupted customers.
ASAI	Average Service Availability Index	The fraction or percentage of time that a customer received power during the defined period.
$CEMI_N$	Customer Experiencing Multiple interruption	CEMIn is the ratio of customer that experience multiple or n-number of interruption and the total number of the customer served.
MAIFI	Momentary Average Interruption Frequency Index	The average frequency of momentary interruption denotes by MAIFI
$MAIEFI_E$	Momentary Average Interruption Event Frequency Index	$MAIEFI_E$ indicates the momentary interruption, average frequency of event excluding events that immediately preceding a sustained interruption.
ASIFI	Average System Interruption Frequency Index	ASIFI indicates the distribution performance in large load concentrated area more specifically industrial or the commercial customer.
ASIDI	Average System Interruption Duration Index	ASIDI is based on load rather than customer, which is the ratio of the duration of connected load and total power served.

2.2 Microgrid

2.2.1 Introduction

According to the history, it could be referred that electrical Microgrid (MG) was first introduced by Thomas Edison in 1882 in Manhattan Perl Street Station when a centralization grid concept was not setup. Later, in 1886 Edison extended his firm with fifty-eight microgrids. Practical research on microgrid in last few years has been drastically increased all over the world, especially in Europe, China, and USA[15].

In the near future, electrical grid will have to face a new challenge to cope with extended demand as well as the secure quality power supply with maximum reliability to the consumers. To overcome the future challenges, the grid must be smarter to run parallel with modern technologies. The Power system should have the ability to facilitate renewable energy resources automatically with high priority, establishing a connection with the end user to ensure secure, quality and reliable energy transfer.

Microgrid is a novel smart grid block or concept which has control over increased various distributed micro generators such as PV array, microturbines with energy storage i.e. flywheel and battery energy storage system. Microgrid control system supports distribution network, optimizes energy generation and usage locally, connection to the upstream distribution network and take control over a downstream network during network fault or other disturbances or hazardous situation through network isolation or islanding mode [16]

2.2.2 Definition

Microgrids is the miniature form of low voltage (LV) or medium voltage (MV) distribution system consisting of distributed energy resources with storage devices such as battery energy storage or flywheels which can be run in non-autonomous and autonomous way in grid-connected mode and islanding mode respectively. Efficient coordination and proper management of microgrids can render definite attainment to the overall power system[17]

Microgrid (MG) is a self-controlled miniature form of power system consisting multiple distributed generation (DG), Energy storage (ES), loads and control devices for a given area which is interconnected directly. Again, microgrid is a platform that allows integration between distributed generators (DG), energy storage system (ESS) and loads and supply quality sustainable and cheap grid power to the consumer [18, 19]

So, the these definition provide few important messages about microgrid which are given below:-

1. Microgeneration, storage units and controllable load located in local distribution grid are integrated via microgrid platform. Although MV network could belong to microgrid, typically microgrid located in LV grid with the capacity of microoperation below the MW range.
2. A microgrid should be operated in both normal state (grid connected) and emergency state (islanding mode) . It is predicted that most of the future microgrid will be operated in normal state for long time. Long-term microgrid operation required high requirements for microgenerators or storage size to supply uninterrupted power to the loads.[17]

2.2.3 Topology of microgrid

Due to the recent development of distributed resources, different microgrid topologies are possible now. Microgrid mainly divided into three types; Ac microgrid, DC microgrid, and AC-DC hybrid microgrid. [20]. Besides these, microgrids cloud be classified based on function demand, capacity and voltage class[19] .Table 2 presents the different types of microgrid based on multiple criteria existing in power system network.

Table 2 :Types of Microgrid based on different criteria

Criteria	Alternatives
Energy types	DC/AC
Connection between large grid	Connected/Not connected
Dispatch able generation	Multiple DER could be performed parallel
Voltage level	Low/Medium
Phase	Single phase /Three phase
Capacity	kW generation/KW of peak load
Load Management	Multiple options
Customer	Single/Multiple

2.2.3.1 DC Microgrid

DC microgrid are getting popularity due to penetration of DC loads and DC storages in houses or industrial buildings for using renewable energy purposes. DC-microgrid reliability could be increased in abnormal situation through special load control mechanism which can disconnect load once load-demand is higher than generation and connect load again while DC bus regulation reach the reference level[21]. A schematic diagram of DC-microgrid is shown in Figure 5 consisting of three different power sources (i.e. Battery energy storage system, wind turbine and PV cells) and DC-AC loads. During low solar irradiation and low wind speeds, battery energy storage system could provide DC power to the DC-microgrid directly to enhance network reliability[22]

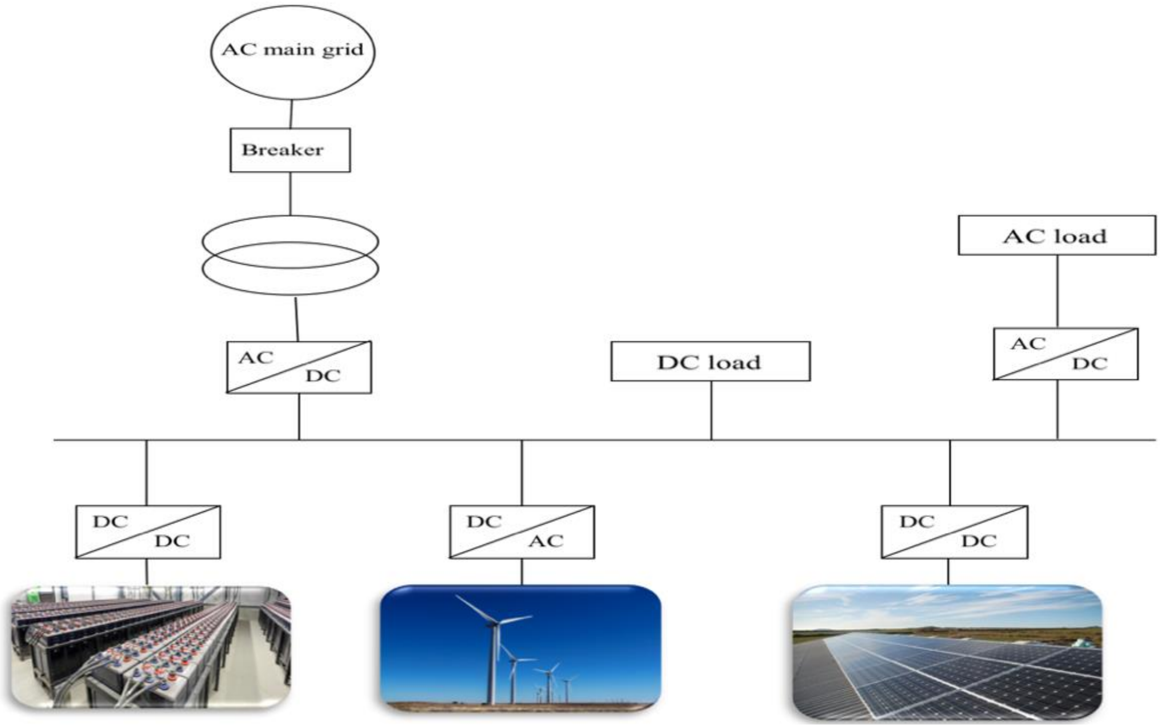


Figure 5: DC Microgrid

a. Extra low voltage

DC microgrid which is designed for voltage level in between 24Vdc to 48Vdc for a small application, home application, IT-office application is called extra low voltage. This microgrid confines to the small area, for example, one tiny room or single office space.

b. Low voltage up to 450 VDC

Low voltage DC microgrid could serve medium power application included HVAC, lighting load of a building. Small or medium size DER could be optionally connected to the low voltage DC microgrid.

c. Low voltage up to 1500 VDC

Low voltage DC microgrid is capable to supply power in DC power distribution, loads and storage system interconnected with high power sources. This microgrid is suitable for industrial and large building with high power demand. [23]

2.2.3.2 AC Microgrid

Distributed Generation (DG) units including a wind turbine, tidal and wave turbines, biogas produces AC power which may connected directly or may indirectly with AC bus line through AC/DC/AC power converter for stable coupling. On the other hand, DG units i.e. solar photovoltaic arrays, fuel cells, and battery storage produce DC power that required DC/AC inverter to connect AC bus line. AC load could be connected directly to the LVAC network whether DC loads required AC/DC converter[24]. A LVAC network could be treated as microgrid while it able to run islanding mode and grid-connected mode[20].A typical AC-microgrid is shown in Figure 6 where load and sources are connected through distinct types of converter.

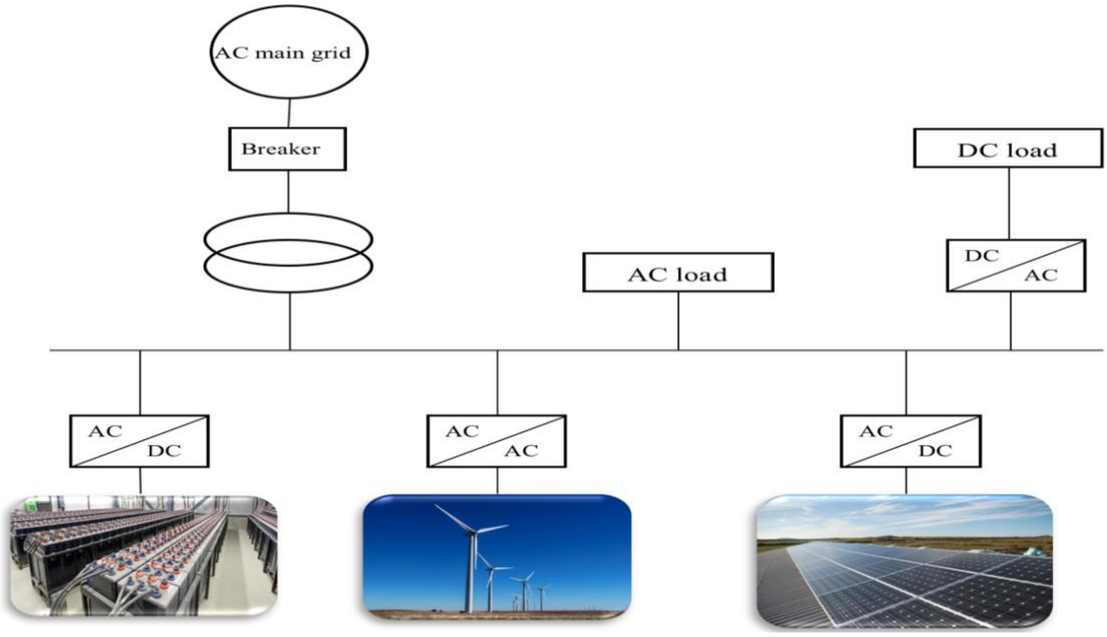


Figure 6: AC Microgrid

2.2.3.3 AC-DC hybrid Microgrid

Three phase AC power system has been dominated the whole power system field over an extended period due to the invention of the transformer and availability of fossil fuel. But modern load characteristic and the distributed renewable generation (GRG) forced to add DC network in grid level. The hybrid grid could be formed in the low voltage distribution network with islanding or interconnected operation with respect to the main utility grid through a transformer. Though there is a standard voltage limit for DC network, 380 V is widely used.[25]. AC-DC micro-grid could be formed with photovoltaic array (PV), wind turbine (WT), biomass fuel, Battery energy storage system (BESS) connected through the power converter. Generally, AC energy resources and DC energy resources are connected to the AC bus and DC bus respectively and build hybrid-DC microgrid [26]. AC and DC both types of load and several types of DER are integrated in hybrid-microgrid which is shown in Figure 7

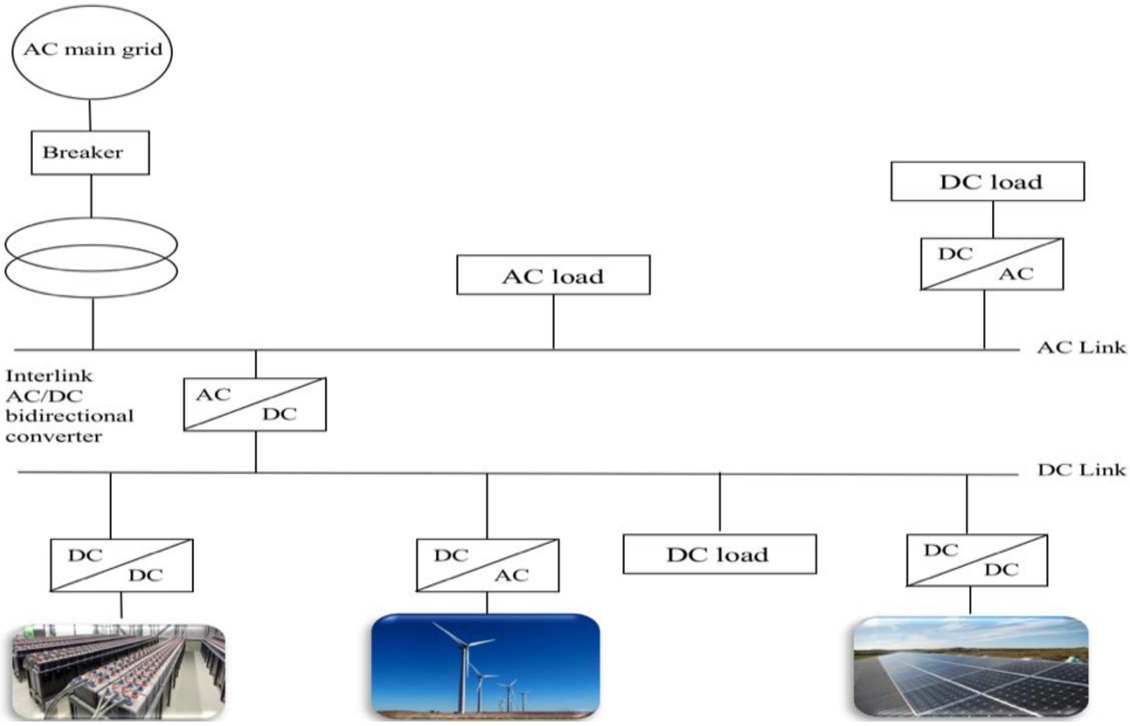


Figure 7: Hybrid Microgrid

2.3 Microgrid protection

Microgrid is the miniature version of main grid consisting of numbers of micro generators which faces the high fluctuation of fault current in the network. Conventional grid protection system could be inefficient in microgrid while power flow or fault current would be bidirectional and topology dependent during abnormal grid conditions[27]. Designing the protection system of the microgrid is one of the major technical issues in the practical implementation of microgrid. The protection system must be capable to protect microgrid in both islanding and normal condition from the fault. Various protection techniques are available for microgrid protection based on different challenges.

The major challenges concerning in the microgrid protection:

- **Dynamic change in fault current:** Microgrid performs normal mode operation connected with LV or MV network while, islanding mode is run without connection with LV or MV network. Fault current is supplied by LV network or MV network along with DGs units during fault condition in grid connected mode which is comparatively higher fault current. On the other hand, in islanding mode operation, fault current supplied by only DGs. So, different magnitude of the fault current should be under consideration to choose fuses in network protection.

- **False tripping:** DGs in nearest substation may supply maximum fault current during fault in neighboring feeder which causes false tripping or unnecessary outage in healthy feeder. Figure 8 shows an example of false tripping due to supply fault current to the neighboring feeder by the DG.

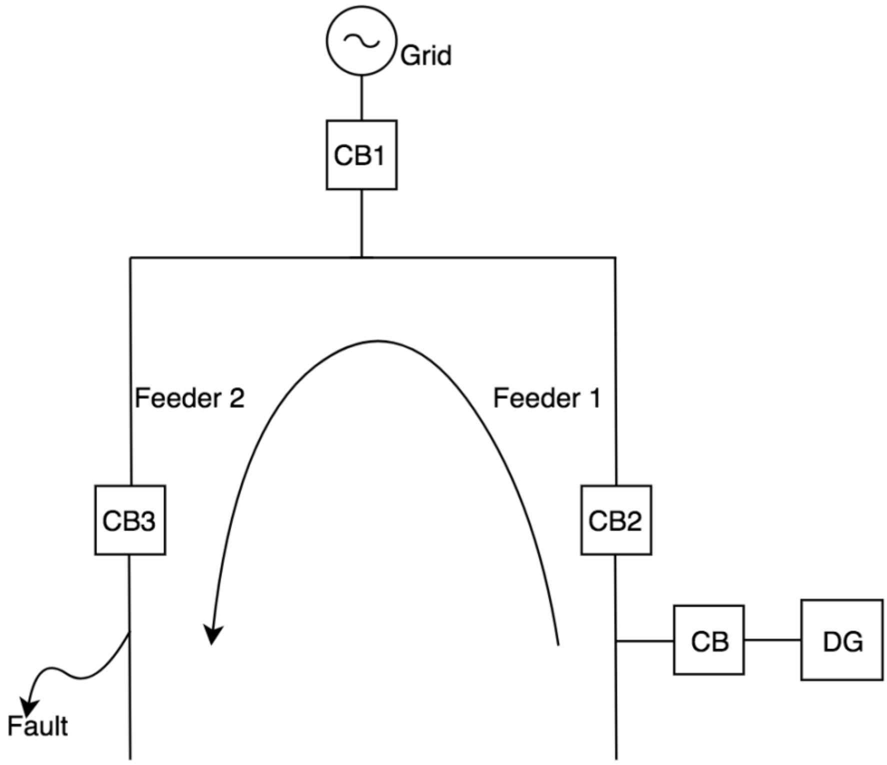


Figure 8 :Fault current supply by DG

- **Loss of main protection:** Loss of main (LOM) protection system is required in microgrid to disconnect microgrid from main grid while fault is occurred in main grid. However, LOM protection is also needed to protect DERs from fault inside microgrid.[28, 29].

- **Blinding of protection:**

Microgrid has the flexibility to switch in both grid connected mode and islanded mode when it required. These operating principals may lead operation error in traditional protection planning for distribution network. Microgrid contributes fault current with the main grid during normal operational (grid connected mode) simultaneously if fault is occurred in downstream of the network. The contribution of fault current changes the real value of total fault current sense by the overcurrent relay and relay stops to trip due to reference value.[30]. In Figure 9 , DG contributes fault current side by side with main utility grid which causes blinding protection in CB1.

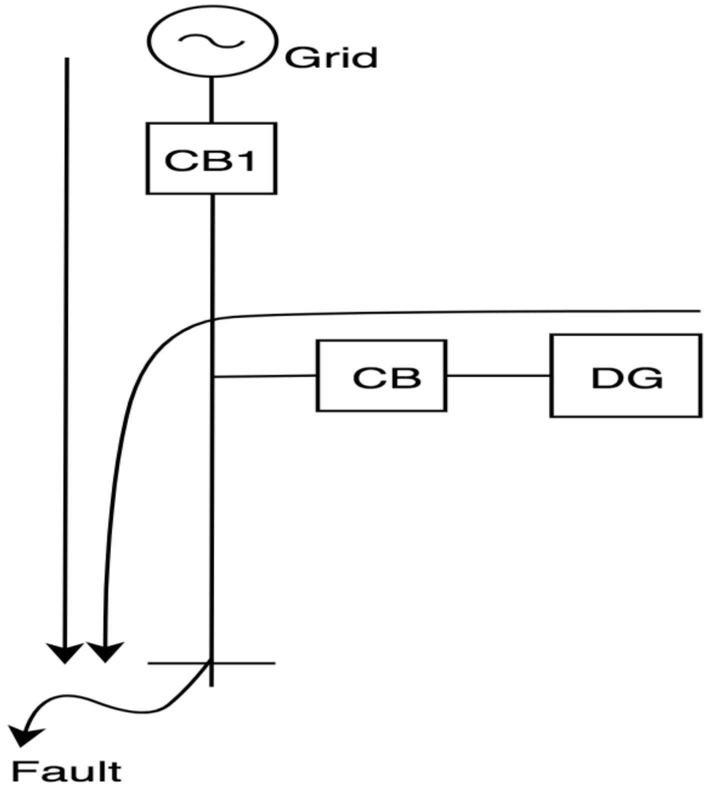


Figure 9: Blinding of protection

2.4 Benefit of Microgrid

Microgrid is a concept of controllable radial electrical system consisting cluster of loads and multiple distributed energy resources (DERs) that provide power to its local area. Normal grid connected operation and islanding operation of microgrid are two different operating modes that bring the flexibility of microgrid. In normal grid connected mode, microgrid is connected to the main grid for supplying power partially from it or taking some power from the main grid based on load-demand response. On the other hand, islanded operation mode is implemented by micro grid central controller (MGCC) to continue power supply to the load inside the microgrid during intentional disconnection (maintenance purposes) or unintentional disconnection (fault occurs) from main grid. Microgrid is connected to the main grid through static switch in point of common coupling (PCC). Microgrid usually disconnected as controllable small grid by opening static switch during fault or maintenance in the grid.[31, 32] Microgrid installation in LV/MV grid could minimize outage duration and faulted customer through islanded operation and keep continuing power supply inside microgrid during upstream interruption.[33]

3. DEVELOPMENT OF ALGORITHM FOR RELIABILITY ANLYSIS OF MICROGRID

3.1 Introduction

This chapter will describe the complete process how to develop algorithms for different reliability index calculation. Fault duration, interrupted customer number, fault location, network fault rate and fault duration are basic parameters for power system reliability determination. Finding connected and disconnected load point during fault clearing, power restoration and in various grid conditions is the first challenge to develop the algorithm. Connected and disconnected nodes are treated as interrupted and uninterrupted loads respectively from the reliability perspective, determined by the graph travers algorithm or graph theory in Matlab. Line fault rate, fault duration and line distance are found from discovered interrupted and uninterrupted nodes that are used in power system reliability determination.

3.2 Graph traverse algorithm

An electrical system requires connection in-between all system components to run the system smoothly with high efficiency. Graph traversal or graph search algorithm has been used to form the distribution network as network tree and helps to find out connected and not connected load points to the root of the tree network. The graph traversal method helps to stablish a virtual connection like a real distribution network through system components such as bus nodes, breaker, and switches. The depth-first search (DFS)and Breath-first search (BFS) both graph searches needed all components are being connected to the network tree to run graph traverse algorithm to the whole network. Graph traverse discovers the all connected vertices or nodes in the tree network which specifies that nodes are not faulted. On the contrary, undiscovered vertices are treated as faulty nodes. Faulted or interrupted customer number, line fault-rate, line distances and corresponding switching time for the faulted nodes are found from network data sheet to calculate reliability indices of the electrical system. Graph traverse algorithm has been used in this research to find out all nodes that are connected to the network to calculate total customers number.

3.2.1 Depth-first search (DFS)

Depth-first search algorithm traverses to the most depth path before exploring the breathed vertex. DFS continues to explore all adjacent and unvisited vertices from the root vertex until it cannot find an unexplored vertex for next transition. The algorithm then follows backtracking through explored vertices to find next uncharted territory and at the end discovers all vertices of the tree network[34] . DFS graph traverse architecture is shown in Figure 10 where DFS starts to explore vertex from the root (1) to the furthest vertex (5) in the first branch and it follows the same pattern for the next all branches of the tree network.

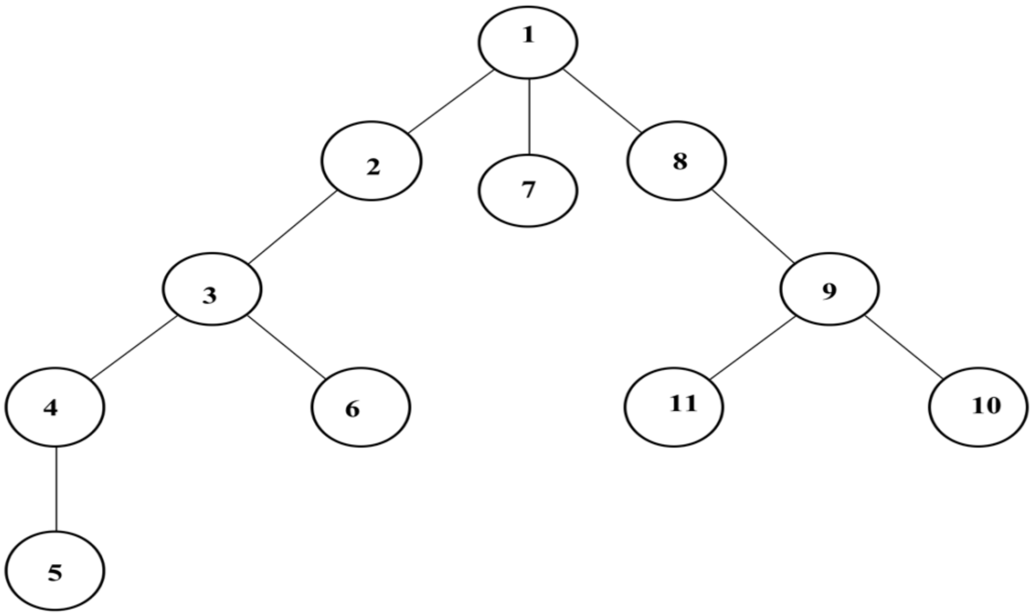


Figure 10 :Depth-first search network topology

3.2.2 Breadth-first search (BFS)

The breadth-first search algorithm is applicable for the tree data structure or network which starts to traverse from the root of the tree and explore the neighbor vertex before exploring the adjacent nodes of the existing branch[35]. BFS graph traverse architecture is shown in Figure 11 where BFS starts to explore vertex from the root (1) to the nearest vertex (2) in the first branch and it follows the same pattern for the next all branches of the tree network.

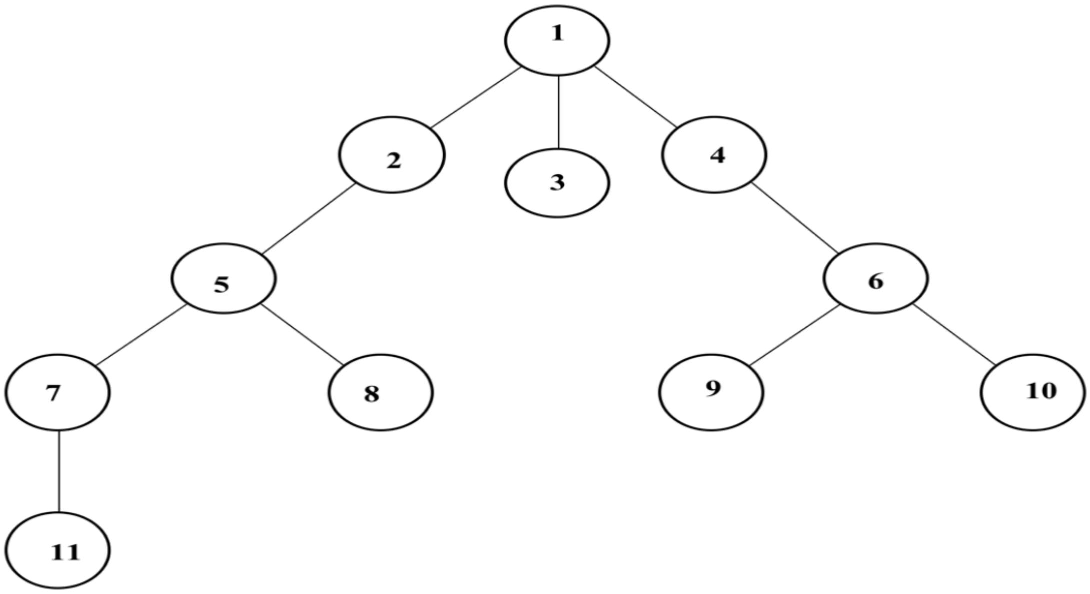


Figure 11:Breadth-first search network topology

3.2.3 Spare matrix

For the grid operation purposes, it must need to keep connected all line nodes and switching nodes to each other in the distribution network. A unique matrix combining of all line nodes and switching nodes have designed to find the length of zero square matrix which present the whole distribution network in symmetrical nodal matrix. Each element of the nodal matrix shows the connectivity status of nodes to each other; 0 for no connection and any other nonzero positive integer or double type data stands for connectivity in between line nodes or switching nodes. Large distribution network may consist of hundreds of line nodes and switching nodes that extend the zero square matrix larger with hundreds of zero elements. Sparse matrix is a special type of mathematical function used to store nonzero logical or double type data elements of a large matrices to speed up the calculation process. Sparse function can reform a full matrix into a full sparse matrix by eliminating all zero elements. Sparse function has been used to represent the logical node connection in two-dimensional sparse matrix [36]

3.2.4 Graph shortest path

Graph-shortest-path function defines the possible shortest path of a N-by-N sparse matrix that represent the whole distribution network. Graph-shortest-path function has been used to minimize the interruption duration of during fault condition. Graph-shortest-path function has been presented bellow-

$$[dist, path, pred] = shortestpath(G, S, T)$$

Here,
G= the spare matrix of logical connection between transmission line, different network switches.
S= The backup connection or Source node from where power supposed to be delivered to the target nodes. This “S” works as root node of the tree network for graph-shortest-path function.
T= ‘’T’’ is presented as target nodes or interrupted customer nodes in the network. T is used to run the graph-shortest-path function to find the shortest path in between source nodes and interrupted customer nodes.
dist= “dist” is the shortest distance between S and T node found from the function.
Path= “Path” shows the nodes which are discovered by the function to reach the target node from root node of the tree.
Pred=Holds the precursor nodes of the path.

Graph-shortest-path function has been used in algorithm to find out the possible shortest path for back up connection to the interrupted customer during fault condition for minimizing the interruption duration. Low interruption duration enhanced grid reliability [37-39]. Developed algorithms have been designed based on such concept to connect all line nodes and switching nodes including normally open (N/O) switches to find out the shortest distance more precisely switching duration during backup power supply to the target nodes in the grid via N/O switch.

3.3 Network tree through graph traverse algorithm

Electrical network data from the Finnish power distribution network has been used in this thesis for analyzing reliability impact over the power system. Graph search algorithm, a novel concept has been applied in power system network to form the virtual connection path between source nodes or battery energy storage (BEES) and load points via switches. In this case, source nodes and BESS connected nodes are treated as a root of the tree network in normal grid operation mode and during islanding mode respectively. The entire process of Tree formation for reliability calculation could be divided into multiple steps. A simple test network is shown in Figure 12 has been taken for describing tree network formation which are given bellow: -

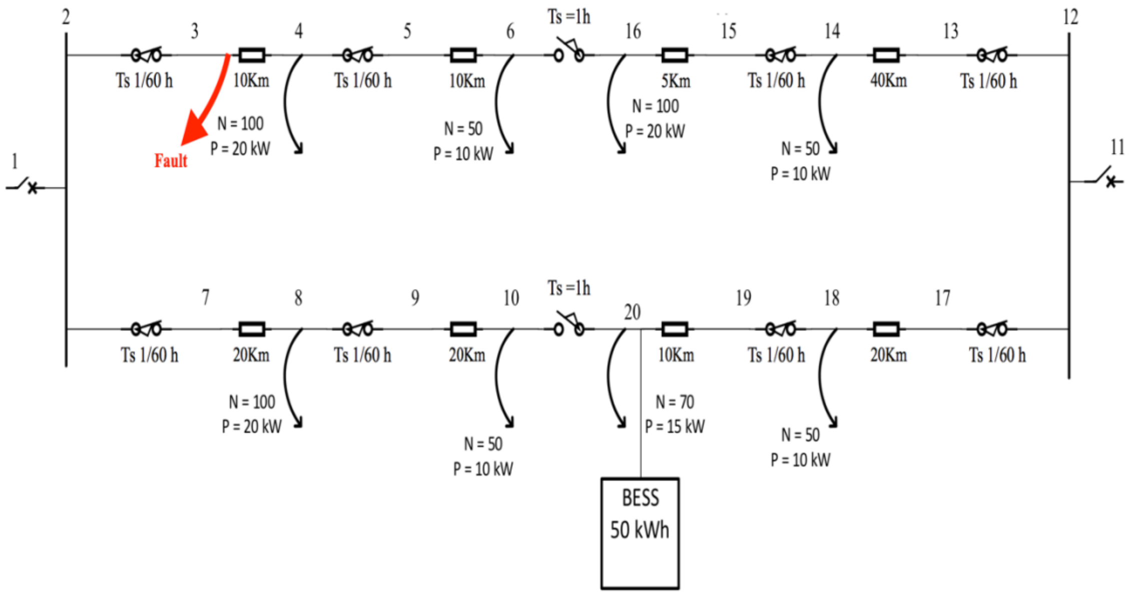


Figure 12:Test network

Figure 12 shows that the test network consists of total 20 nodes including two auxiliary power supply source nodes (1 and 11) connected through grid protection relays (1-2, 11-12) ,8 transmission line each segment having individual loads, 8 normally closed (N/C), 2 normally open (N/O) switches and one BESS connected at node 20. The test network has been presented as tree network by biograph-object matlab function in Figure 13. Biograph object is a data structure holding interconnected collective data to create a graph directly. Spares matrix is used as interconnected collective data here to depict the tree network. Here, node 1 and node 11 used as source nodes to the network. N/O switches will remain open before any fault occurred in the system.

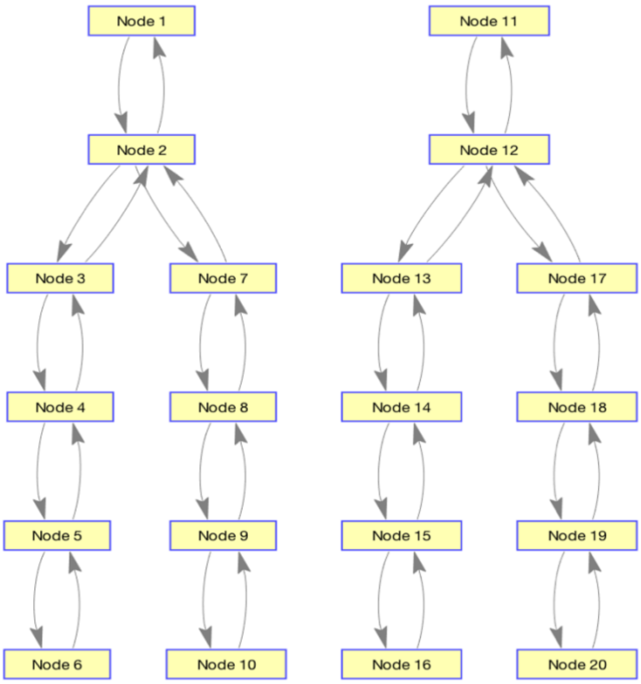


Figure 13: Tree formation of the test network

1. Fault clearing

When there is a fault in the grid, fault should be cleared as soon as possible to protect the grid from extreme damage caused by fault current. Figure 14 depicts the tree network of the test network while fault is already cleared from the network. Each fault in grid forces to open the grid protection relay which causes short interruption for the load points. The algorithm has been developed in such way to open or disconnect all N/C switches that relate to faulty transmission line to prevent rest of the network from fault damage. Node 3 and node 4 is treated as permanent fault nodes due to presence of fault in the line. Moreover, Node 5 and Node 6 will suffer long duration interruption due to having only chance of routing power supply through N/O switches with long switching time. Rest of the nodes will face only short interruption duration due to fault in first branch. This method causes short interruption to the all load points in the faulted feeder excluding fault ride through (FRT) protected nodes. After fault clearing, network is tried to restore by the auxiliary power supplies or backup sources to the maximum possible load points.

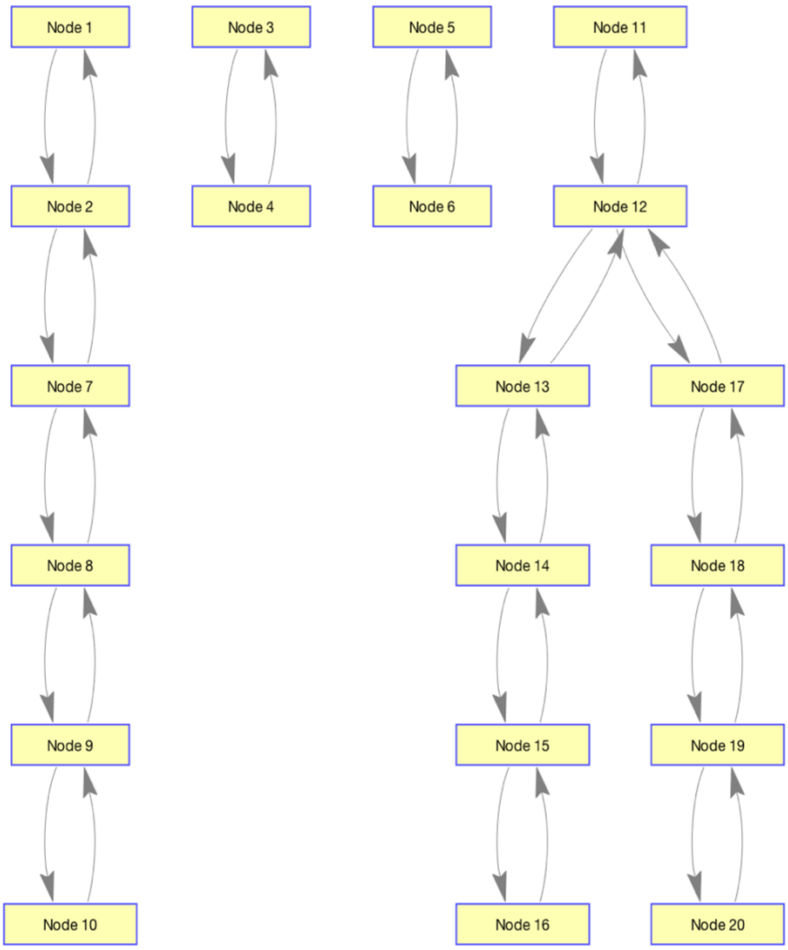


Figure 14: Possible connection to the load points

2. Network restoration

During network restoration, developed algorithm has been given priority first to feed the distribution network through auxiliary power supply. Load points those are suffering for long duration interruption or treated as permanent fault due to unavailability of backup connections are taken in consideration for microgrid operation to minimize interruption duration. Power supply is restored in node 5 and node 6 shown in Figure 15 and Figure 16 via N/O switches result long duration interruption. Power supply to the node 5 and node 6 from node 1, has to follow longer feeder compare to power supply from node 11 shows in Figure 16. Developed algorithms give priority to the possible shortest feeder and simplest distribution grid topology (in this case radial) to make sure possible lowest interruption duration for the interrupted customers. So, in this case power supply from node-11 is accepted.

BESS installation in long duration interrupted customer has given in second priority to minimize the outage duration. Node 3 and node 4 will remain disconnected until fault repair is completed, and all customers connected to these nodes will suffer interruption duration as long as fault repair is required.

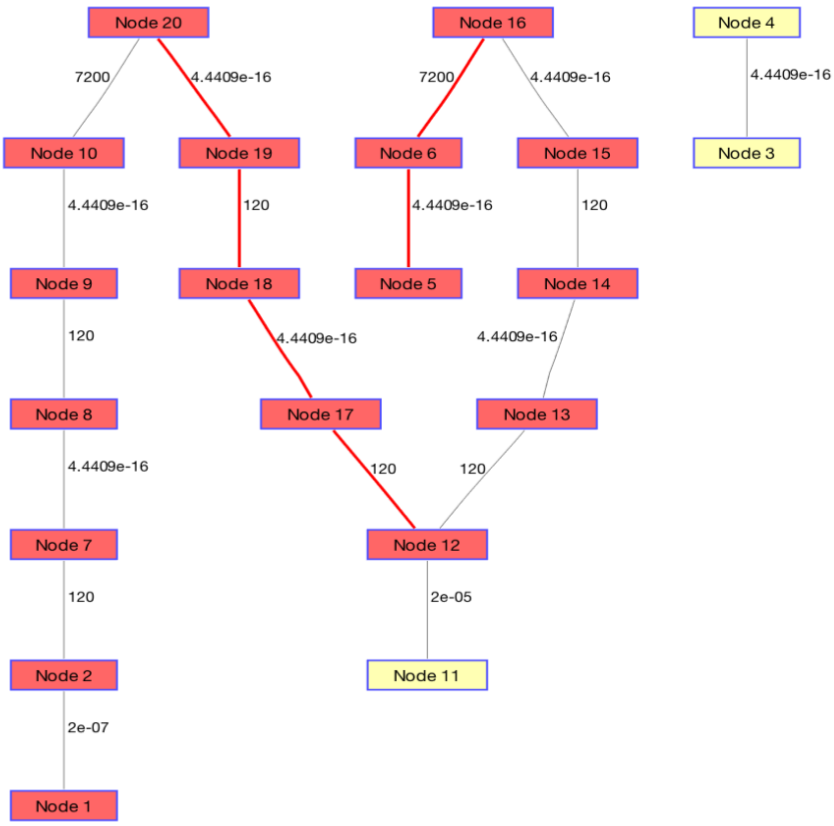


Figure 15: Power supply restoration through node 1

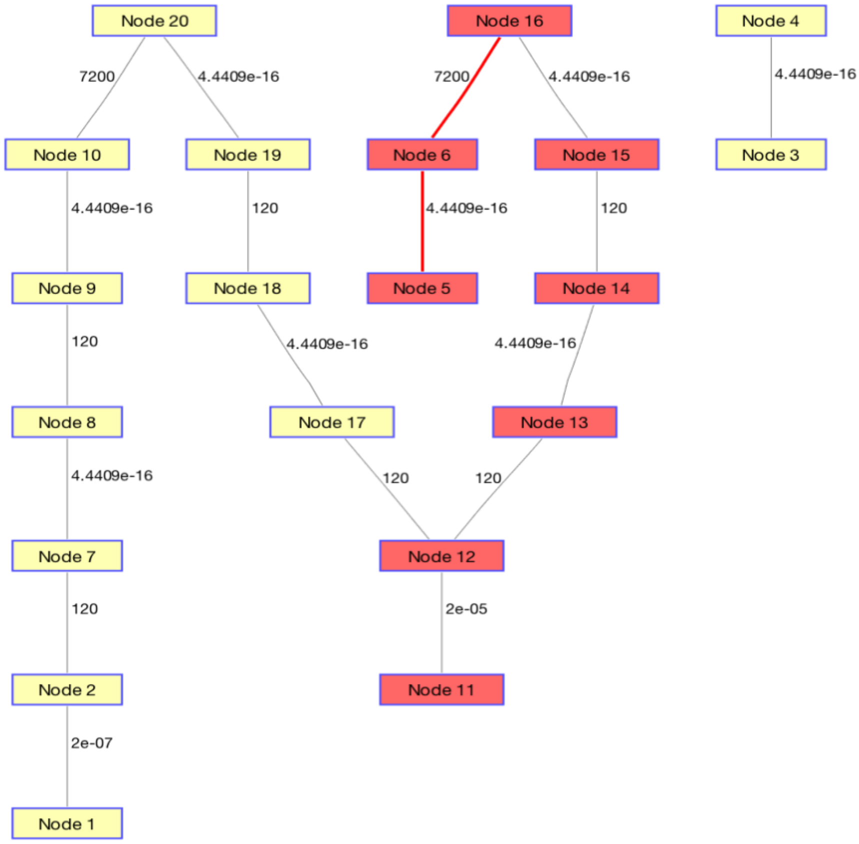


Figure 16: Power supply restoration through node 11

3.4 Mathematical expression for reliability indices

This thesis deals with two reliability indices SAIFI and SAIDI to analysis the reliability impact of microgrid in distribution grid. Mathematical explanation of SAIFI and SAIDI have been given below

Mathematically SAIFI could be expressed [40]

$$\boldsymbol{SAIFI} = \frac{\boldsymbol{\sum Total\ number\ of\ sustained\ Intrruption}}{\boldsymbol{Total\ number\ of\ customer\ served}} \quad (4)$$

Now,

$$Total\ number\ of\ sustained\ Intrruption = Total\ number\ of\ faulty\ customers$$

Again, SAIDI could be mathematically expressed [40]

$$SAIDI = \frac{\sum Total\ outage\ duration\ for\ all\ interrupted\ customer}{Total\ number\ of\ customer\ served} \quad (5)$$

Here,

$$Total\ outage\ duration\ for\ all\ interrupted\ customer = \sum(\lambda * parmanent\ faulted\ customer * repair\ duration) + (\lambda * temporary\ faulted\ customer * switching\ duration) \ldots\ldots\ldots\ldots (6)$$

Where, $\lambda = line\ distance * fault\ rate.$

3.5 Algorithm development in different gird condition

In this research, four cases have been chosen for developing algorithm to illustrate grid reliability. The result found from four different cases help to analysis the reliability of distribution network.

1. SAIDI determination in auxiliary power supply mode.
2. SAIFI determination in fault ride through condition.
3. SAIDI determination in nominal microgrid condition.
4. SAIDI determination in maximum microgrid support condition.

The basic ideas and differences among these four cases are given briefly below: -

In auxiliary power supply mode, multiple backup power supply sources have been applied while BESS supply is unavailable in the grid.

In fault ride through condition, SAIFI has been determined in the grid while fault ride through capability is available in BESS supported microgrid in the grid.

In nominal microgrid condition, SAIDI has been determined while BESSs are able to support its own load points only.

In maximum microgrid support condition, SAIDI has been determined while BESSs are able to support possible maximum interrupted load points based on total BESSs capacity of a microgrid.

3.5.1 SAIDI determination in auxiliary power supply mode.

SAIDI indicates the total interruption duration of the average customer during the predefined period. Equation 2 shows the mathematical expression of SAIDI, where total outage duration is the key variable for SAIDI value. Auxiliary power supply or multiple backup power source could be desirable choice to shorten outage duration hence improve the overall system reliability[41] . It has been assumed that in auxiliary power supply mode, the distribution network was supplied by multiple source nodes or backup nodes situated in different location in grid. In this research, five fixed backup power sources have been selected to analyze the impact of auxiliary power supply on network reliability. It also assumed that each source can handle the total load of the network.

A complete process of developing algorithm for SAIDI determination for single fault in auxiliary power supply condition is sequentially shown by the flow chart in Figure 17. In the very beginning of the process, virtual network tree of the distribution network has been developed using switching nodes and line nodes data. In section-C, line fault is taken place in transmission line sequentially in the network. The condition checking box in section-D will check the fault location for each line fault to extend the process for the next fault. Section E and F in Figure 17 find different type (long-term, short-term, permanent) of interrupted load points using graph theory and determine the SAIDI for the corresponding fault respectively. In the last step, SAIDI for the network has been determine by adding SAIDI value for each line fault in the network.

It has been assumed that the probability of fault in different transmission line is fixed. So, the entire process has been repeated for each line fault and total SAIDI of the whole network finally determined.

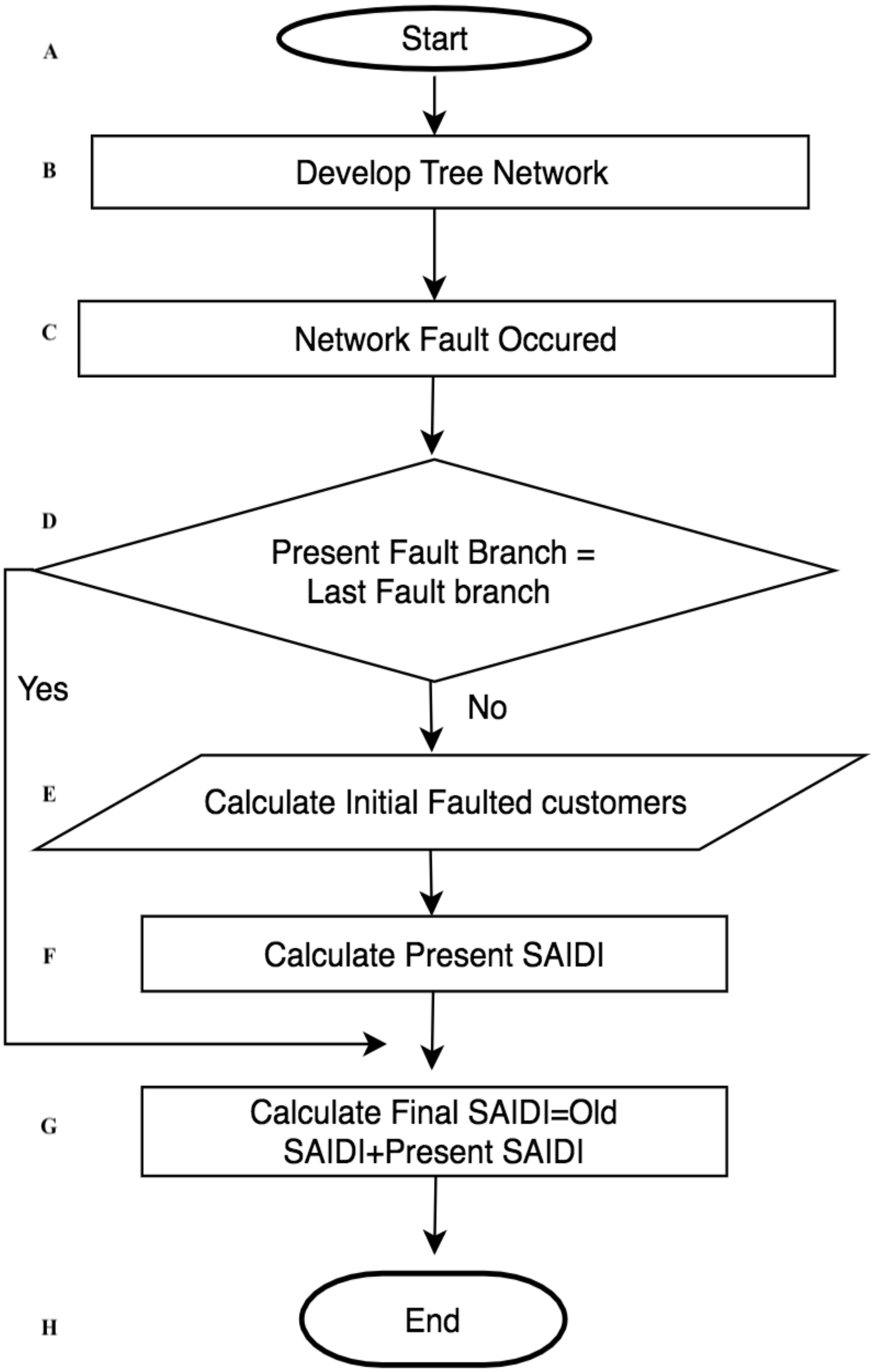


Figure 17: SAIDI determination in auxiliary power supply mode

```
2   %Graph traveres required sparse matrics
    G_saidi_islanding = sparse( G_saidi_islanding );
4   %Pr_Fault_Node_indexs are parmanent faulted nodes search by Depth-
    first search algoritm.
6   Pr_Fault_Node_index = graphtraverse( G_saidi_islanding,
    Fault_Node_Index);
8   %Pr_Faulted_Cust_number denotes the total number of customar that
    sense the parmanent fault
10  Pr_Faulted_Cust =sum( cell2mat(CUST( ...
        ismember( CUST(:,1),Pr_Fault_Node_Name ),2)));
12  Lamda = Line_Length / 1000 * ...
       LINETYPE{ ismember(LINETYPE(:,1),Line_Type),7};
14  Fault_Repair_Time= LINETYPE{
    ismember(LINETYPE(:,1),Line_Type),8}/60;
16
    SAIDI=SAIDI+((Lamda.*Pr_Faulted_Cust.*Fault_Rpair_Time)+(Lamda.*lon
    gtime_customer.*Manual_SW_Tf)+(Lamda.*
    shortime_customer.*Short_sw_time))/Total_Cust_Number;
```

Program 1

Program 1 shows the coding sample of SAIDI determination algorithm. In 2nd line, `G_saidi_islanding` stands for sparse matrix which is used later to develop tree network as well as for finding initial faulted nodes for each fault in the grid. `Pr_Faulted_Cust` and `longtime_customer` stands for total number of faulted customer and customer those have been suffered long duration outage due to the fault. `CUST` is cell array including all customer details of the network (customer number, load demand and connected node name) used to determine the total customer number or faulty customer number reliability calculation. The used Finnish distribution network transmission lines have divided in three categories based on fault rate. `LINETYPE` is cell array holding all details (fault rate, line distance, fault repair time) of three types transmission line. `Fault_Repair_Time` has been used to find fault repair time for each specific line fault from the provided data xl-file. `Manual_SW_Tf` and `Short_sw_time` provides manual switching time and auto reclosing time for long period interrupted customer and short-period interrupted customers respectively during grid isolation and restoration. `Lamda` has been determined multiplying line distance with line fault rate found from the data sheet using `LINETYPE`.

3.5.2 SAIFI determination in fault ride-through condition

Fault ride through (FRT) capability is the DGs ability of supplying power to the utility grid network to enhance the grid performance for certain level of voltage and time[42]. Fault ride through capability helps to overcome the interruption of power supply to the customer through communication-based dual time-current-voltage protection system[43] It has been assumed that the BESSs have been installed with FRT capability to continue uninterrupted power supply to BESS supported load points during short-term outage due to any fault in grid. SAIFI is proportional to the interrupted customer number directly for a specific transmission line (fault rate, line distance, fault repair time remain fixed) if total customer number is constant. So, increasing BESS availability will shorten interrupted customer number hence improve the overall network SAIFI.

Figure 18 shows the entire process of determination of SAIFI in fault ride through condition. Firstly, section A-C in flow chart developed the tree network using network data and

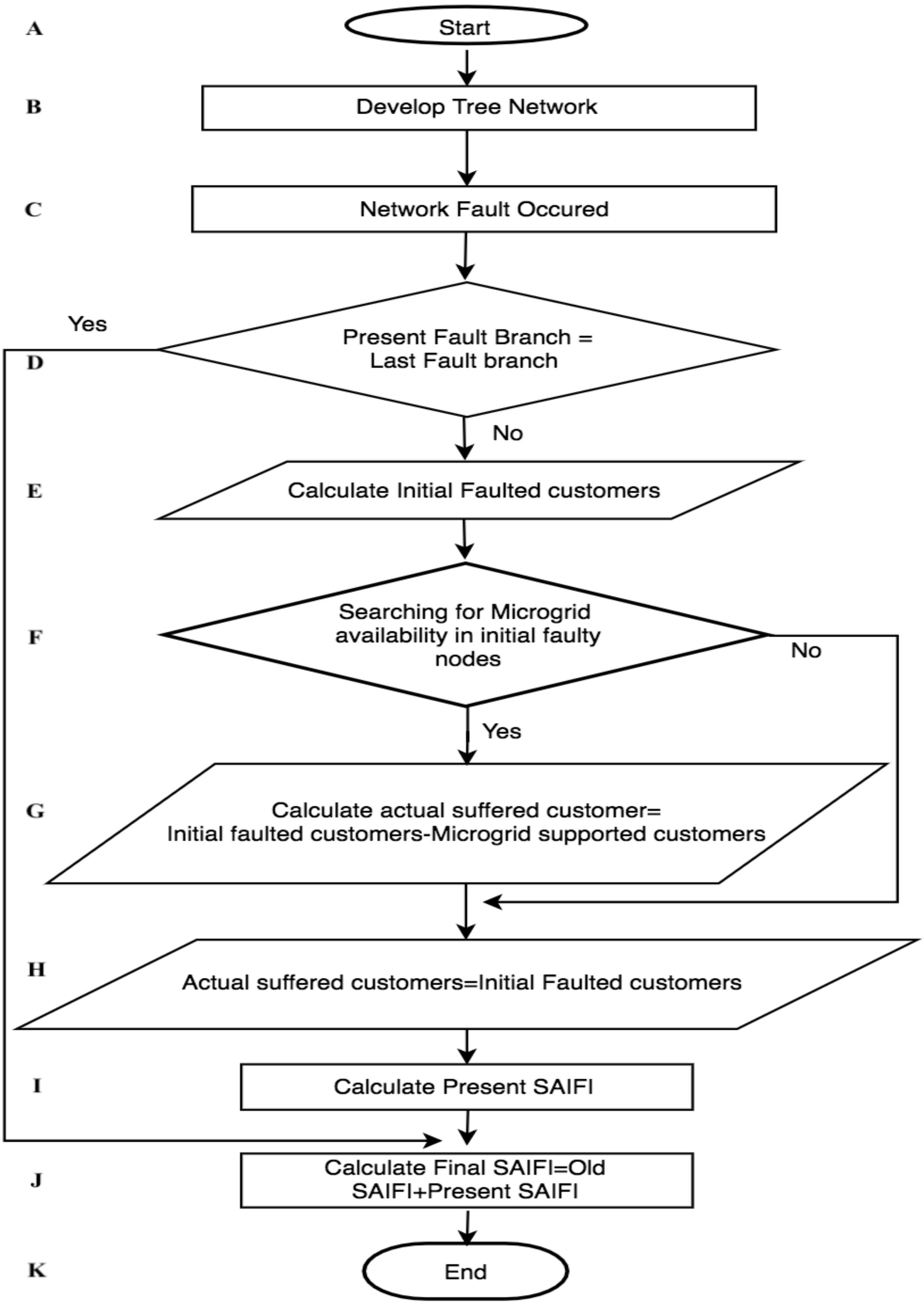


Figure 18: SAIFI determination in fault ride through condition

integrates fault to the transmission line. Fault location is checked by the condition checking box in section D and later initial or primary faulted customer determined by the faulted nodes at section E in Figure 18 . Algorithm now starts to check the BESS supported nodes which is shown in second condition checking box at section F in Figure 18 Updated faulty customers have been determined through deducting BESS supported customer due to FRT condition. In last step, SAIFI has been calculated for the complete system based on actual suffered customer number repeating the entire process.

```
   G_saifi = sparse( G_saifi );
2      % Determining indices of the nodes which experience the
   fault...
4   FaultNodeIndices = graphtraverse( G_saifi,
   LineBeginNodeIndex );
6
   NFaultyCustomers = sum( cell2mat( CUST( ...
8           ismember(CUST(:,1),FaultNodeNames ),2)));
   LineFaultRate = LineLength / 1000 * ...
10         LINETYPE{ismember(LINETYPE(:,1),LineType),7};
   NFaultyCustomers =NFaultyCustomers- BESS_supported_Cust;
12 TotalNCust = sum(cell2mat( CUST(:,2) ) );
   % Incrementing SAIFI:
14 Calculate_SAIFI          =          Calculate_SAIFI          +
   NFaultyCustomers/TotalNCust * LineFaultRate;
```

Program 2

Program 2 shows Matlab functions which are used to develop the algorithm of SAIFI determination in fault ride through condition. "`G_saifi`" is the sparse matrix for tree network and "`NFaultyCustomers`" defines the total interrupted customer for each line fault. "`BESS_supported_Cust`" is used to show the total number of BESS supported uninterrupted customers. `LineFaultRate` is found from provided XL-data sheet using `LINETYPE` data variable in matlab. `TotalNCust` counts the total customers connected in the network. Line 14th of the Program 2 shows the SAIFI determination of the system.

3.5.3 SAIDI determination in nominal-microgrid condition.

It has been assumed that each BESS capacity of a specific load point is able to handle the total load that connected in the same node for the outage duration. Here, only long-term interrupted nodes due to unavailable auxiliary or backup supply path could be supported through BESS as microgrid state. As BESS can support the total load of a load point, BESS supported customer of the load point will suffer less outage duration than before. According to the SAIDI calculation equation, SAIDI value directly proportional to the total outage duration for the all interrupted customers in a grid. Now, total outage duration depends on permanent faulted customer and temporary faulted customer including switching duration shown in equation 6. The nodes which are connected to the transmission line or faulty part of the grid are treated as parament faulted nodes. Parament faulty nodes and connected customers have bound to face outage as long as repair time is required to repair the fault. Again, temporary faulted customers are consisting of long term interrupted and short-term interrupted customers based on switching time. So, BESS supported long-term interrupted nodes will face only short-period interruption caused by grid relay operation or optimum switching time hence over all long-term interrupted customer including overall outage duration of the grid will be minimized.

Figure 19 illustrates the flow chart of SAIDI determination in nominal microgrid condition. Tree network has been formed from the line and switching data at the beginning of the process. Sections C to F Figure 19 shows that connected and disconnected nodes have been found out using the tree network. In section-G, condition box checking the BESS availability in long-term interrupted nodes to introduce microgrid facility to shorten outage duration of the nodes. Temporary faulted nodes or customers have been updated at section-H in the flow chart. Finally, section-J calculates SAIDI values for a particular fault based on updated total outage duration for all interrupted customers in the grid. The entire process is required to repeat to determine the total SAIDI of the network.

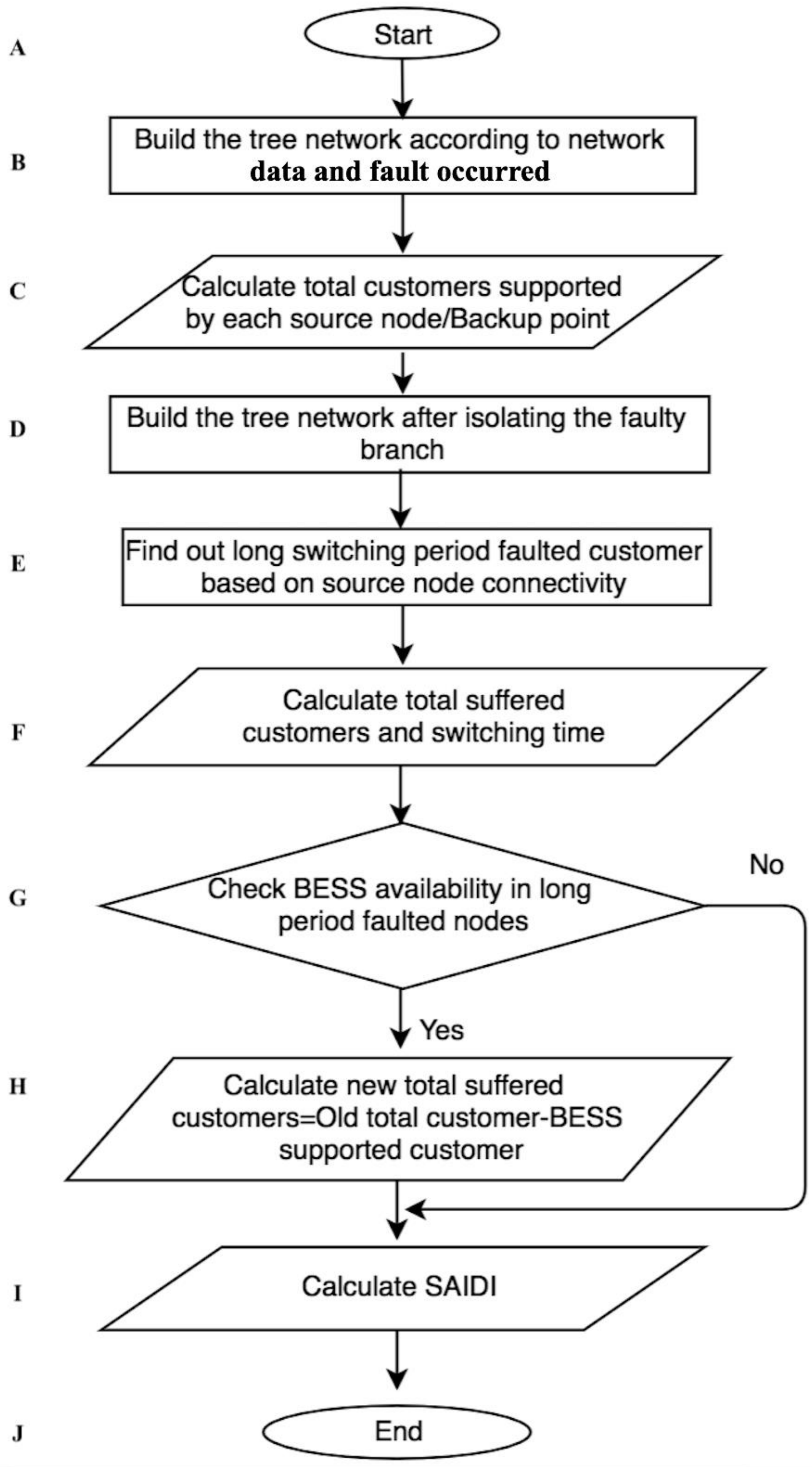


Figure 19: SAIDI determination in nominal microgrid condition

```
   % sparse matrics is defined for  Graph traveres
2  G_saidi_islanding = sparse( G_saidi_islanding );
   %Pr_Fault_Node_indexs are parmanent faulted nodes search by
4  Depth-first search algoritm.
   Pr_Fault_Node_index = graphtraverse( G_saidi_islanding,
6  Fault_Node_Index);
   Pr_Fault_Node_Name = node_names( Pr_Fault_Node_index);
8  %Pr_Faulted_Cust_number denotes the total number of customer
   that sense the parmanent fault
10 Pr_Faulted_Cust_initial=sum( cell2mat(CUST( ...
      ismember( CUST(:,1),Pr_Fault_Node_Name ),2)));
12 %Checking BESS availability
    if max(chk_bess)==1
14 Pr_Faulted_Custi =Pr_Faulted_Cust_initial;
      else
     Pr_Faulted_Custi
16 =(Pr_Faulted_Cust_initial+sum(cell2mat(CUST(ismember(CUST(:,1),Op
   en_node),2))));
18  End
   %Checking the BESS position
20 Check_BESS_In_Shortpath=ismember(Short_time_faulted_node_name,BES
   S_Nodes_In_Backup_path(b,1));
22     if max(Check_BESSIN_FaultedBrance)==1
         BESS_Suported_Cust=0 ;
24    elseif max(Check_BESS_In_Shortpath)==1
         BESS_Suported_Cust=0;
26    else
   %BESS_Supported_customer denotes the customer are backuped by
18 BESS
   BESS_Suported_Cust=sum(cell2mat(CUST(ismember(CUST(:,1),BESSsupor
30 tedNode_name),2)));

32 Total_Cust_Number = sum( cell2mat( CUST(:,2)));
   %SAIDI increment
34 SAIDI=SAIDI+((Lamda.*Pr_Faulted_Cust.*Fault_Repair_Time)+(Lamda.*
   longtime_customer.*Manual_SW_Tf)+(Lamda.*
   shortime_customer.*Short_sw_time))/Total_Cust_Number;
   SAIDI_Final=SAIDI
```

Program 3

Program 3 shows the sample program for SAIDI determination in nominal microgrid condition. "`G_saidi_islanding`" has been defined as sparse matrix for graph traverse algorithm to build the tree network. "`Pr_Faulted_Cust_initial`" and "`Pr_Faulted_Custi`" denotes total permanent faulted customer before BESSs installation in long-period interrupted nodes and total updated permanent faulted customer before BESSs installation in long-period interrupted nodes respectively. "`Check_BESS_In_Shortpath`" and "`chk_bess`" are used for checking BESS availability in between faulted nodes in the grid. "`BESS_Suported_Cust`" calculate the total BESS supported customer number. Line 32 to 34 in Program 3 show the total SAIDI calculation for the grid.

3.5.4 SAIDI determination in maximum-microgrid-support condition

Maximum-microgrid-support concept has been designed based on assumption of supporting through BESSs to the possible highest number of interrupted customers during fault condition. In this case, BESSs can supply to the multiple load points based on its's storage-demand capacity. BESSs will only support to the nodes those are treated as permanent faulted nodes due to unavailable backup source path. The concept of supporting accessible multiple load points though single or multiple BESSs have decreased overall interruption duration and interrupted customer number for the grid. It has been also assumed that microgrid protection system is autonomously well equipped to run islanding and grid connected mode when its required.

Figure 20 shows the flow chart of determination process of SAIDI in maximum power supply condition. The starts with developing tree network and setting up fault in grid through section A to B in the flow chart. Section C is used to determine the short-period interrupted customer which are fed by the auxiliary of backup supply. Section D to F show the process to determine the long-period interrupted nodes. Condition checking box in section G checks the BESS availability in long-term interrupted nodes for initiating microgrid support. If the condition is “false” then long-period interrupted customer will remain as same as before. But if the condition is “true”, algorithm continue to the next step. In next checking box checks the total BESSs storage limit compare to the total loads for supporting further load points. Higher load demand compare to the BESS capacity makes the condition “false” and proceed final SAIDI determination. Lower load demand compares to total BESSs make the condition “true” and long-term interrupted nodes are supported by the BESSs. Section I in Figure 20 updates the interrupted customer and proceed to the final step of SAIDI calculation.

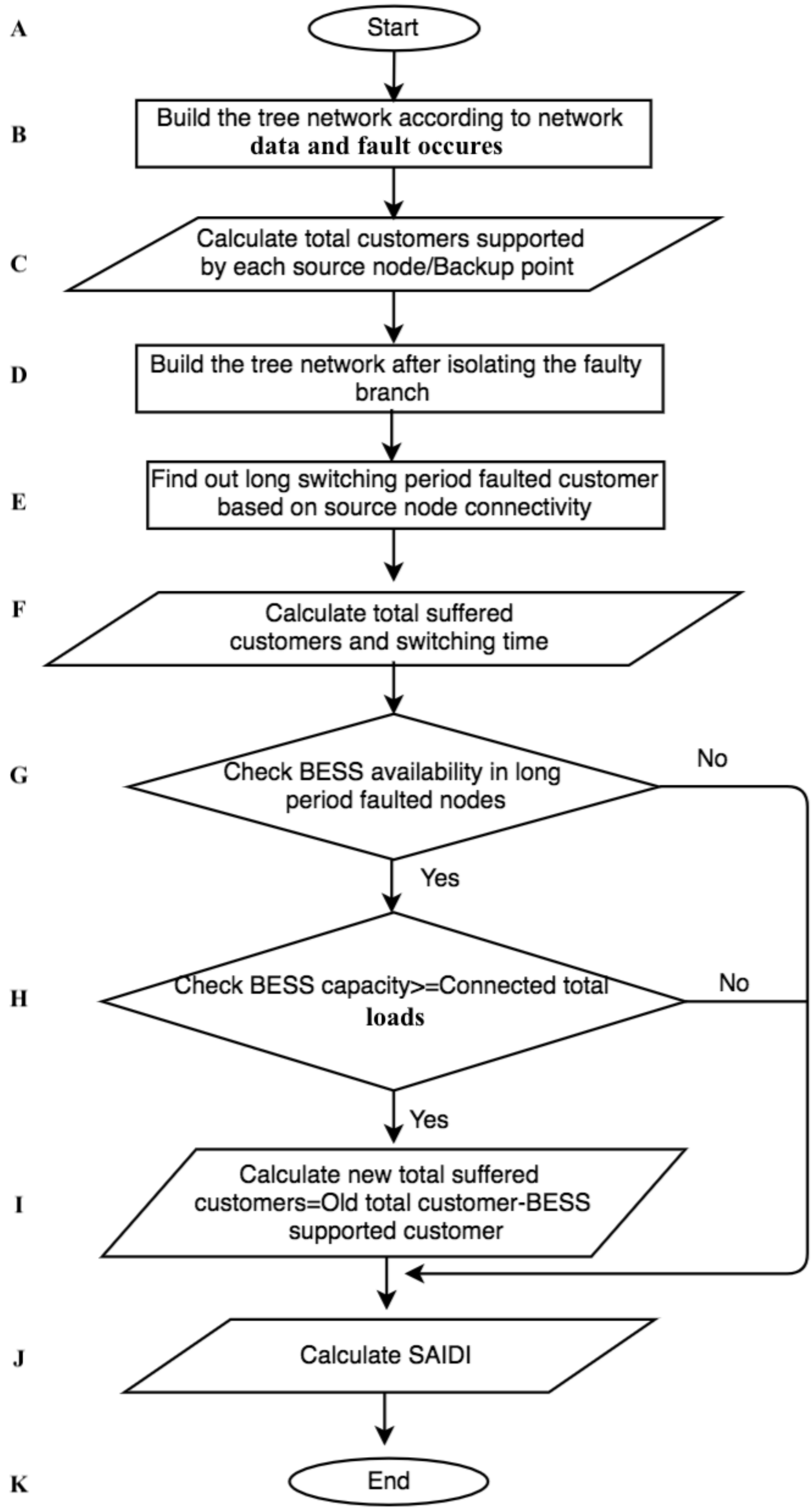


Figure 20: SAIDI determination in maximum microgrid support condition

```
   %Graph traveres required sparse matrics
2  G_saidi_islanding = sparse( G_saidi_islanding );
   %Pr_Fault_Node_indexs are parmanent faulted nodes search by
4  Depth-first search algoritm.
   Pr_Fault_Node_index = graphtraverse( G_saidi_islanding,
6  Fault_Node_Index);
   Pr_Fault_Node_Name = node_names( Pr_Fault_Node_index);
8  %Pr_Faulted_Cust_number denotes the total number of customer
   that sense the parmanent fault
10 Pr_Faulted_Cust_initial=sum( cell2mat(CUST( ...
      ismember( CUST(:,1),Pr_Fault_Node_Name ),2)));
12
   for k=1:size(Connected_load_InfaultyZone,1)
     c=Cust+cell2mat(Connected_Cust_InfaultyZone(k,1));
14   Cust=c;
    %Pr_Faulted_Custi denotes the permanent faulted customer
16  Pr_Faulted_Custi =Pr_Faulted_Cust_initial+
   (sum(cell2mat(CUST(ismember(CUST(:,1),Loaded_open_node),2)))-
18 Cust);
   %Support to the maximum faulty customers upto BESS capacity
20   if (BESS_Capacity_InfaultyZone==Total_load_InfaultyZone)
             break
22     end
   end
24  %Checking the BESS position
   Check_BESS_In_Shortpath=ismember(Short_time_faulted_node_name,B
26 ESS_Nodes_In_Backup_path(b,1));
       if max(Check_BESSIN_FaultedBrance)==1
28        BESS_Suported_Cust=0 ;
      elseif max(Check_BESS_In_Shortpath)==1
30        BESS_Suported_Cust=0;
      else
32 Total_Cust_Number = sum( cell2mat( CUST(:,2)));
   %SAIDI increment
34 SAIDI=SAIDI+((Lamda.*Pr_Faulted_Cust.*Fault_Repair_Time)+(Lamda
   .*longtime_customer.*Manual_SW_Tf)+(Lamda.*
   shortime_customer.*Short_sw_time))/Total_Cust_Number;
36 SAIDI_Final=SAIDI
    end
```

Program 4

Program 4 shows the Matlab coding of determination of SAIDI in maximum microgrid support condition. "`G_saidi_islanding`" in first line used for sparse matrix which is needed to develop tree network and "`Pr_Faulted_Cust_initial`" and "`Pr_Faulted_Custi`" used to show the initial and updated parament faulted customers in the grid. "`BESS_Capacity_InfaultyZone`" and "`Total_load_InfaultyZone`" stands for total BESS capacity and total load respectively connected in a same branch in the grid. Line 24th to 30th of the Program 4 check the BESS availability and determine the BESS supported customer. Line 32nd to 36th show the final SAIDI calculation for the grid in maximum microgrid support condition.

4. RESULT AND ANALYSIS

4.1 Introduction

This chapter deals with comparative result analysis found from the distribution network using developed algorithms. Multiple case studies have been chosen for determining the reliability indices for the network. Grid connected mode and microgrid mode are two major areas to apply all case studies. This research also explains about the impact of multiple auxiliary power sources, BESSs number, change of nominal fault duration, and change of nominal fault rate over the network reliability. The research illustrates the change of the reliability indices of a real distribution network during various condition for example normal grid operation mode, auxiliary power supply mode, fault ride through condition, nominal microgrid condition and maximum microgrid power supply condition. All case studies could be presented as follows: -

a. **Grid connected mode.**
   1. Auxiliary power supply mode.

b. **Microgrid mode with five auxiliary connections**
   1. Impact of fault ride through (FRT) capability of microgrid over power distribution network.
   2. Impact of nominal microgrid condition over power distribution network.
      - Impact of BESS number on reliability indices.
      - Impact of BESS positioning in the grid on reliability in the system. BESS position has been chosen based on three categories; Most faulty load point, high density load point and randomly selected load point.
      - Impact of nominal fault rate and fault duration on system reliability while BESS number is constant.
   3. Maximum microgrid power supply condition.
      - Impact of BESS size on grid reliability
      - Impact of nominal fault rate and fault duration on system reliability while BESS size is fixed.

4.1.1 Sensitivity analysis

Sensitivity analysis of a distribution network reliability is the method to calculate the amount of change of reliability indices with respect to reliability indices parameter such as fault rate, fault time and DER size[44]. Sensitivity analysis could be conducted through practical or simulated results. In this research, simulation results based on different nominal fault rate, nominal fault duration, BESS size, BESS number and BESS positioning in the grid have been used for sensitivity analysis.

4.2 Grid connected mode

Initially, it has been assumed that the distribution network has been supplied radially through one source node at a time during grid connected mode operation there is no any available BESS for microgrid operation. SAIFI and SAIDI value have been calculated as 3.1788 h and 4.2261 respectively in these conditions. The main goal of the thesis is to search lower SAIFI and SAIDI value for the distribution system to improve the grid reliability.

4.2.1 Auxiliary power supply mode

Impact of multiple auxiliary power sources on reliability index (SAIDI) has been shown in Figure 21. Line graph depicts that initially distribution network has higher value for SAIDI while one backup connection is available for the grid. It also illustrates how SAIDI is affected in the system due to multiple backup source connection.

As can be seen from the graph, SAIDI value has been decreased while number of backup connections has been increased in the network. It also shows that, initial SAIDI value has around 4.22 h/a which sharply decreased by around 3.3 h/a and became almost steady or saturated at around .92h/a while third auxiliary connection has been installed. Backup connection shortens the interruption duration as well as interrupted customer number during fault condition. Short interruption and less faulted customer shorten the SAIDI value which is clearly shown in Figure 21. So, the simulation results conclude that multiple backup sources for the distribution grid enhance overall grid performance or grid reliability

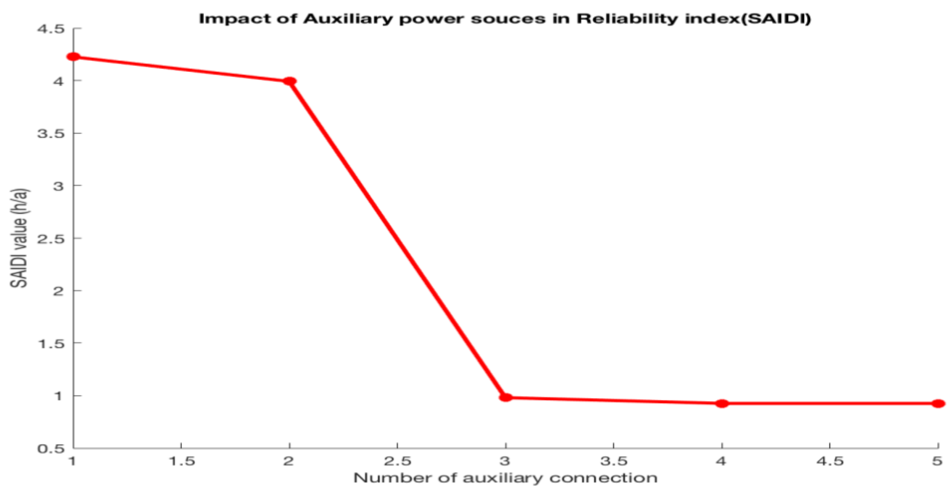


Figure 21: Impact of auxiliary power sources in grid reliability

4.3 Microgrid Mode with five auxiliary connections

In microgrid condition, five auxiliary or backup sources are applied along with BESS. BESSs are used as microgrid backup sources and it is assumed that each BESS can carry the connected load at the same nodes. It has been also assumed that BESSs are connected through microgrid protection system. Initially, BESS connected nodes have been chosen randomly with twenty set of nodes each set holds seventeen nodal data to see the network reliability performance.

4.3.1 Fault ride through (FRT) condition

Fault ride through (FRT) functionality of microgrid helps to continue uninterrupted power supply to load during fault condition. So, in fault condition momentary interruption will not be sense by the microgrid supported nodes which affects overall grid SAIFI. On the other hand, SAIFI stays unchanged due to the presence of momentary interruption in grid while FRT is unavailable in microgrid. It is depicted in Figure 22 that SAIFI stays unchanged though number of BESS has been increased in the grid. SAIFI of the distribution network stays constant with respect to the BESS number in Figure 22. So, there is no effect of microgrid on grid SAIFI if FRT capability is unavailable.

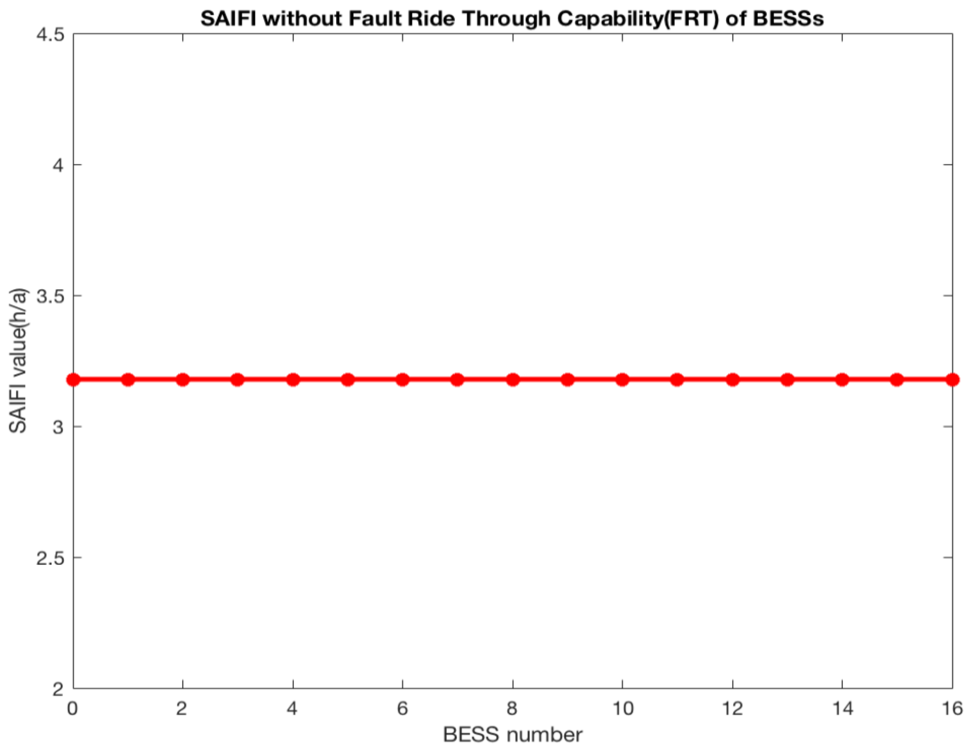


Figure 22 Network SAIFI without FRT capability

On the other hand, multiple BESSs help to overcome momentary interruption in distribution system which results lower interrupted customer number as well as shorten interruption duration in the grid. Lower interrupted customers and short interruption duration improve overall network SAIFI and SAIDI shows in Figure 23

Figure 23 shows the rate of change in percentage for SAIFI and SAIDI with respect to the increased BESS number in the grid. BESS positions have been chosen randomly in the grid and for both cases, BESS quantity have enormous influence on SAIFI and SAIDI. It is clearly shown in Figure 23 that SAIFI and SAIDI both curves follow almost similar pattern.

SAIFI and SAIDI both improved sharply at first BESS installation. It has been also seen that SAIDI and SAIFI improvement stays constant from 2nd to 12th and 5th to 12th BESS respectively which means SAIDI and SAIFI values reach to the saturation level at these BESS points for the network. This case study illustrates that BESS installation in these nodes will be less effective over network reliability performance though the overall grid reliability enhanced.

So, the lines graph concludes that FRT capability of microgrid has an overall positive impact on grid reliability if microgrid location chosen in right way.

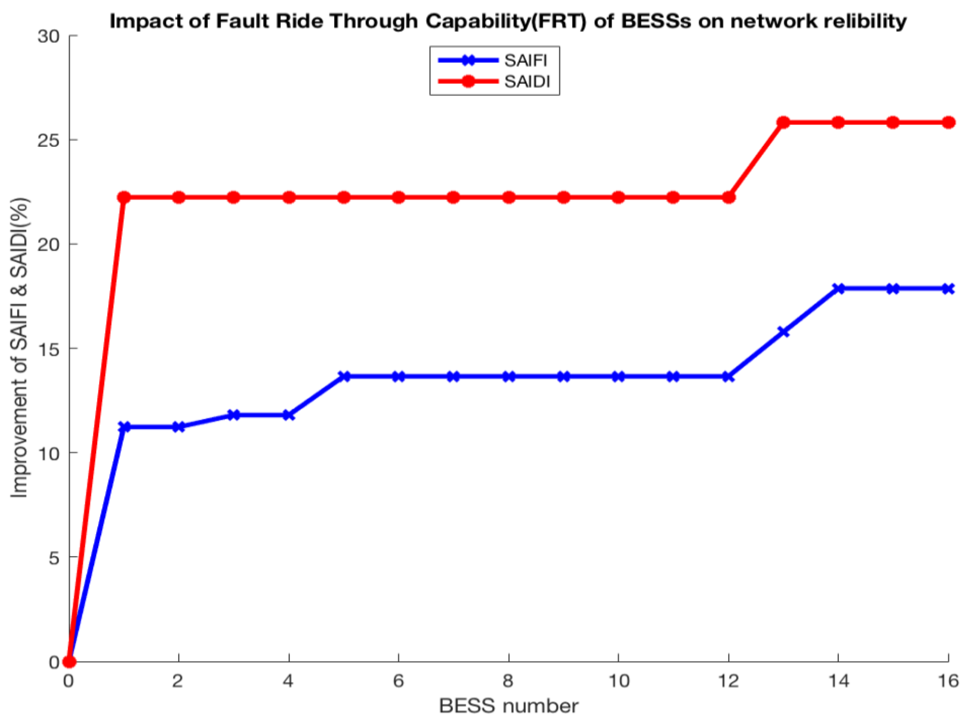


Figure 23: Network reliability with FRT capability

4.3.2 Nominal Microgrid condition

- **BESS installation at most faulty nodes and high-density load points:**

In nominal microgrid condition, 16 most faulty or vulnerable load points and 16 densely loaded nodes have been selected for BESS installation to observe the impact of BESS number on grid reliability. Figure 24 shows the line graphs drawn by the simulated results found from the network.

It has been shown that there is no effect of BESSs on SAIDI before 4th BESS installation in the grid. BESSs in these nodes has no effect on reliability index (SAIDI) due to absence of long interrupted customers for microgrid supports through BESS. The line graph illustrates that same number of BESS installation in most faulty nodes improve the grid reliability relatively higher than BESS installation in densely loaded nodes in the grid. Figure 24 also depicts that grid reliability index has been reached to the saturation point after 13th BESS installion in the grid.

So, the line graph concludes that microgrid support for a certain number in distribution network could improve network reliability.

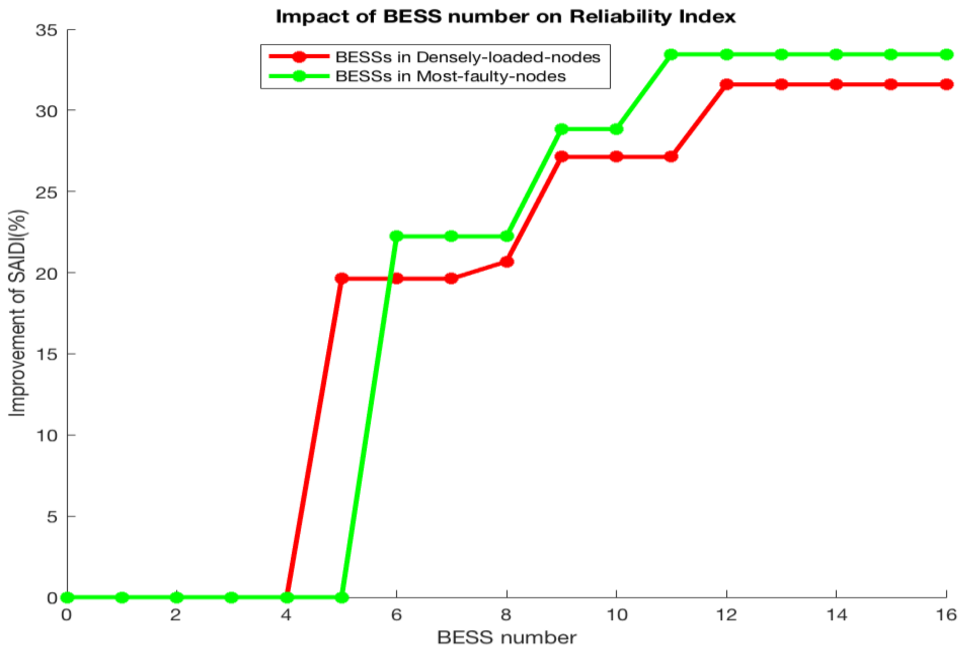


Figure 24: Impact of BESS number in grid reliability

- **Impact of change in nominal fault rate while BESS number and nominal fault duration is remained constant**.

Figure 25 shows the change of SAIDI values with respect to the change of nominal fault rate from 0 to 140% through three-line graphs. SAIDI values have been determined in the presence of 18 BESSs in densely-loaded nodes and most-faulty nodes in the grid. Moreover, SAIDI also recorded without any BESS in the grid.

In the below curve, grid has highest SAIDI values when BESSs are unavailable in the grid. In the presence of BESSs in both most faulty nodes and densely loaded nodes, SAIDI values are almost similar. However, the behavior of the curves with increase of nominal fault rate was identical.

Hence, it can be determined from the Figure 25 that the absence of BESSs results in an undesirable increase of SAIDI values, thereby making the network less reliable. With regards to the presence of BESSs, the desirable network is the one that depicts a lower set of SAIDI values, i.e. the network with the faultiest nodes, in comparison to the network with densely loaded nodes.

As the microgrid does not have any impact on grid fault rate, BESSs will be less effective near to the saturation level of grid reliability. In Figure 25 , benefit of BESSs are decreasing slowly compare to without BESS case due to having no impact of microgrid on nominal grid fault rate.

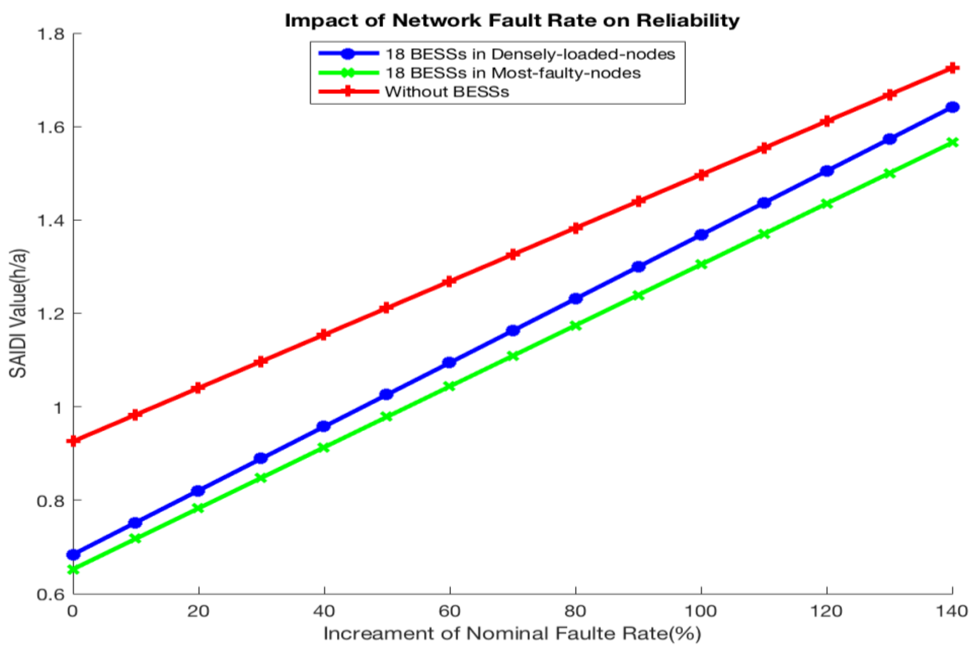


Figure 25: Impact of fault rate on reliability index during nominal microgrid state.

- **Impact of change in nominal fault duration while BESS number and nominal fault rate is constant**.

The line graph in Figure 26 depicts the change of SAIDI values with respect to the change of nominal fault duration to 140% in three different restraints, BESSs in high density loaded nodes, BESSs in most faulty nodes and in the absence of BESSs.

The line graph illustrates that SAIDI values without BESSs is much higher than the values with BESSs. In the presence of BESSs, for both faulty nodes and densely loaded nodes, the SAIDI values are similar. However, the behavior of the curves with increase of nominal fault duration is identical.

Hence, it can be determined from the Figure 26 that the absence of BESSs results in an undesirable increase of SAIDI values, thereby making the network less reliable. With regards to the presence of BESSs, the desirable network is the one that depicts a lower set of SAIDI values, i.e. the network with the faultiest nodes, in comparison to the network with densely loaded nodes.

As the microgrid helps to shorten the fault duration, BESSs have significant impact on overall outage duration of the grid hence impact on overall grid reliability index (SAIDI). In Figure 26 , benefit of BESSs are increasing slowly compare to without BESS case due to having impact of microgrid on fault duration.

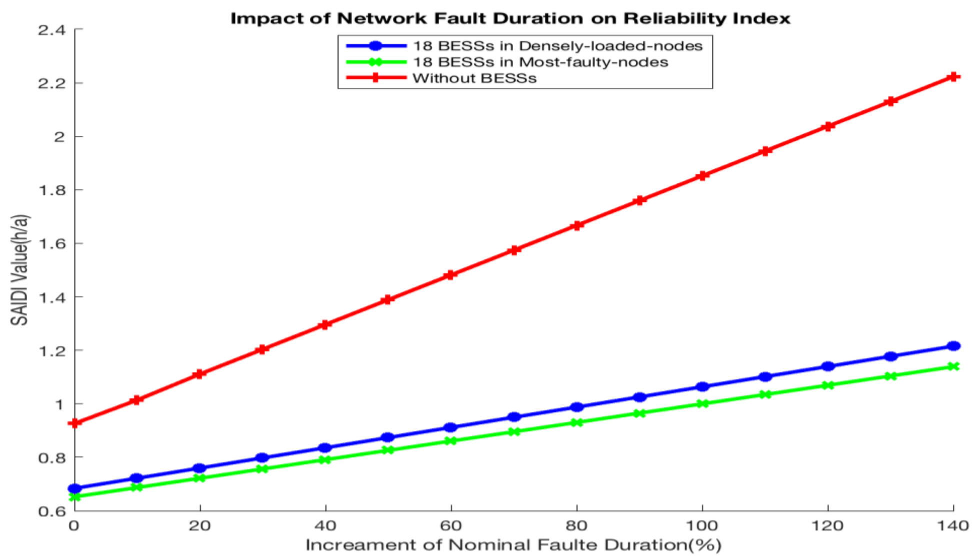


Figure 26: Impact of fault duration on reliability index during nominal microgrid state.

- **BESSs installation in randomly selected load points**.

Figure 27 shows the multiple line graphs, each line graph presents the change of SAIDI values for each set of randomly selected eighteen nodes in the grid during nominal microgrid condition. Form the graph, it is clearly shown that for all seventeen sets of nodes having initial SAIDI value around .925 h/a and sharply decreased by around .15 h/a with respect to increasing BESS installation in the grid.

Heterogonous line graph for each set of randomly selected nodes defines the impact of BESS positioning on reliability index for a grid. Figure 27 shows that SAIDI doesent improved for some set of BESS locations after two or even multiple BESSs installing in the grid. The trend of line graphs conclude that BESSs installation in right location is important from the perspective view of grid performance enhancement.

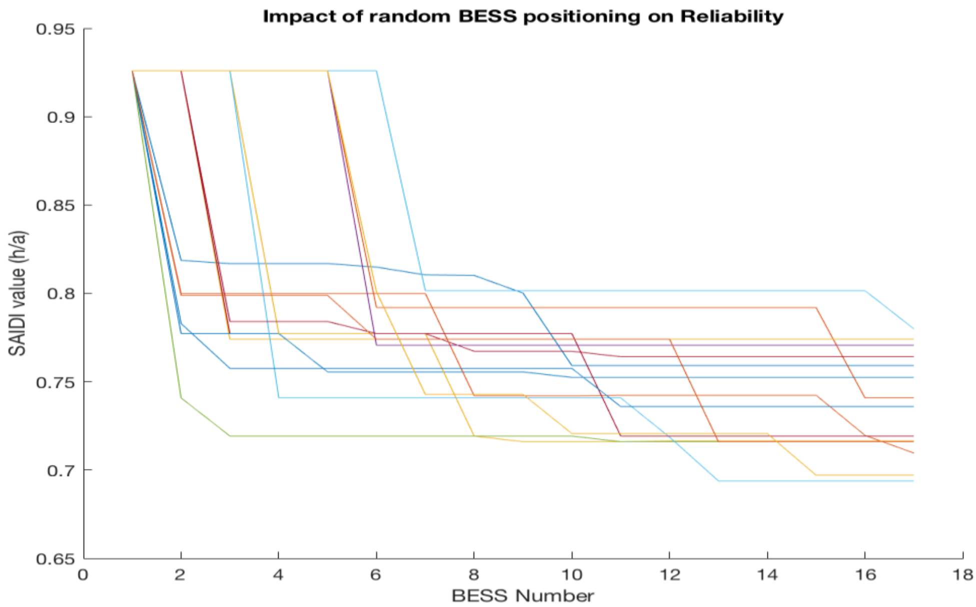


Figure 27: Impact of random BESS positioning on grid reliability

4.3.3 Maximum Microgrid power supply condition

1. **Impact of BESS size in grid reliability**

Figure 28 shows the improvement of SAIDI in percentage with respect to the 14 BESS size from 0 to 14 kWh thorough line graphs. Regarding the both line graphs trend, the improvement of SAIDI is increased due to higher BESS size in both types BESS location (high densely loaded node and most faulty nodes) have positive impact on grid reliability.

BESS availability in most faulty nodes has relatively higher impact on overall SAIDI compare to BESS availability in densely loaded nodes due to frequent microgrid supports to the long-interrupted nodes in most faulty nodes during each fault in the grid. However, both curves have almost similar pattern. Two different line graphs in Figure 28 indicate that increasing BESS capacity in most interrupted nodes helps heals the gird performance faster than BESS installation in high density loaded nodes.

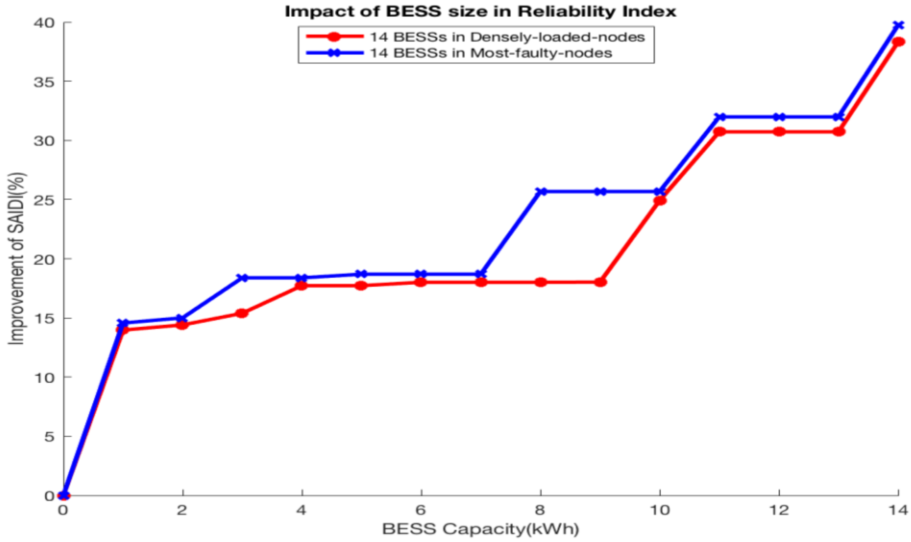


Figure 28: Impact of BESS capacity in grid reliability

2. **Impact of change in nominal fault rate while BESS capacity and nominal fault duration is constant.**

Figure 29 shows the SAIDI results with respect to the change of nominal fault rate 0 to 140% in the presence of 14 BESSs (13kWh/BESS) in both most faulty nodes and densely loaded nodes kin the grid. SAIDI values are increased for both cases for increased nominal fault rate in the grid. From the line graph it could be said that SAIDI values increased almost double for 60% increment of nominal fault rate in the grid.

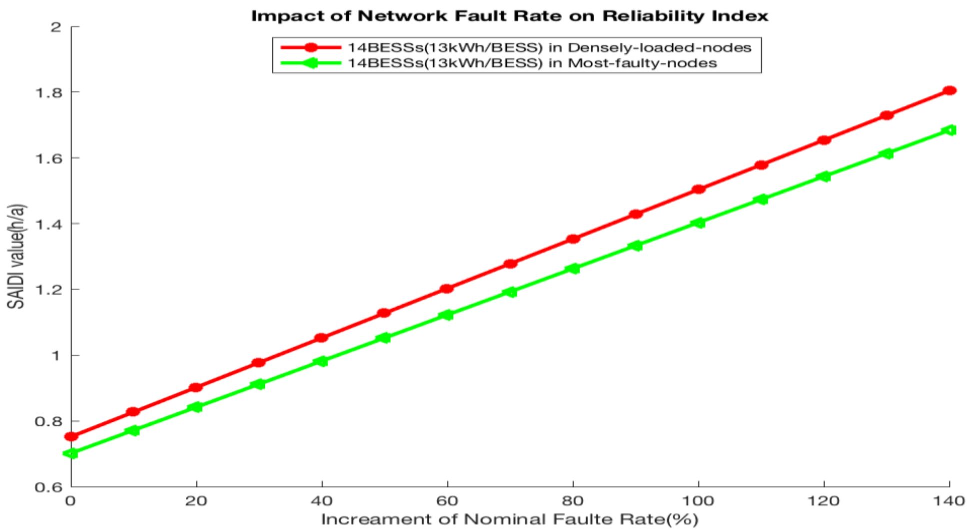


Figure 29:Impact of fault rate on reliability index during maximum microgrid power supply condition

3. **Impact of change in nominal fault duration while BESS capacity and nominal fault rate is constant**

Figure 30 shows the SAIDI results with respect to the change of nominal fault duration 0 to 140% in the presence of 14 BESSs (13kWh/BESS) in both most faulty nodes and densely loaded nodes kin the grid. SAIDI values are increased for both cases for increased nominal fault duration in the grid.

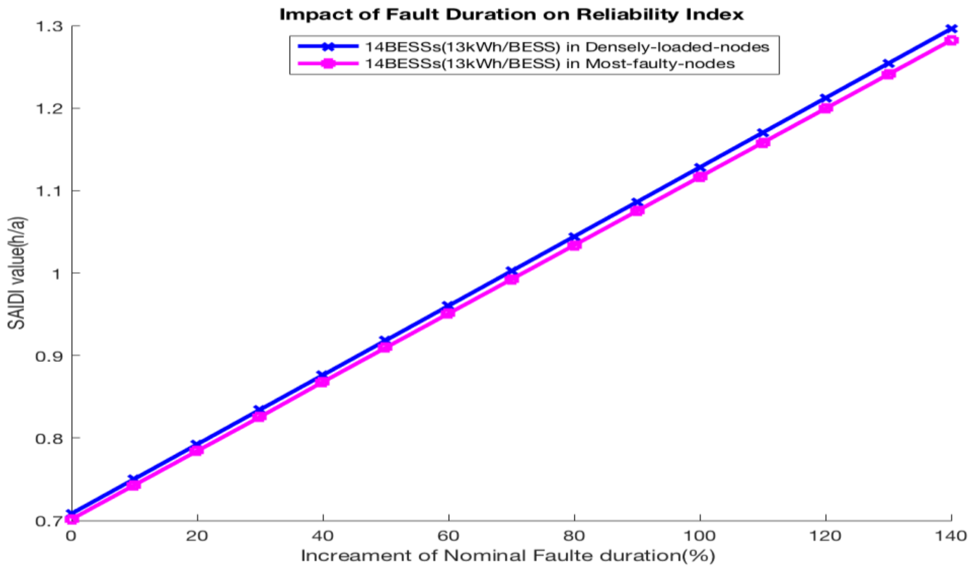


Figure 30: Impact of fault duration on reliability index during maximum microgrid power supply condition

4.4 Discussions

Applied all case studies are developed based on two major grid operations, i.e. grid connected mode and microgrid mode or islanded mode to see how theses case studies affect the reliability of the grid.

The research results suggested that multiple backup connections for grid supply during fault condition have improved overall grid reliability index (SAIDI). Extra four auxiliary power supply sources decreased the SAIDI value by around 3.3 h/a. So, this research results also state that more auxiliary power sources increase the possibility of improvement of grid reliability.

Simulated SAIDI and SAIFI results in section 4.3.1 have clearly distinguished the impact of fault ride through (FRT) capability of microgrid over grid reliability. FRT capability of microgrid helps to improve SAIFI around 17% compare to without FRT though the rate of improvement is also depending on BESSs location in the grid. This research findings state that FRT capable microgrid have overall positive impact on grid reliability.

Nominal microgrid condition case study shows that, overall reliability index (SAIDI) have been improved with respect to increasing BESS installation in grid for all case studies in section 4.3.2. The simulation result shows that BESS installation in each most faulty-nodes, high-density-loaded nodes and randomly selected nodes have different impact on grid reliability which emphasis the importance of choosing right BESS location. Finding the suitable BESS locations through iterative method to maximize grid reliability is needed as an extended research of this thesis. The research results summarize that more available microgrid provide overall better grid performance compare to less available microgrid in the grid in nominal microgrid condition.

SAIDI values in maximum microgrid condition also improve with respect to increasing BESS capacity for a fixed number of BESS in the grid. Increment of BESSs capacity have improved SAIDI up to around 39% of nominal value. So, the research findings suggest that grid reliability could be increased by increasing BESSs capacity.

5. CONCLUSIONS

Grid reliability of distribution power system is one of the major concerning issues from the perspective view of economic and uninterrupted power supply to the loads. The main target of this thesis is to determine reliability indices in different grid condition to understand the impact of a microgrid in grid reliability.

In first case, SAIDI have been determined for the grid with five auxiliary power sources. The impact of auxiliary power source over network reliability have been well understood. Multiple auxiliary power sources in separate multiple locations in the grid shorten interruption duration due to connectable available backup sources. So, backup power sources or auxiliary power source could be one possible option for the grid reliability enhancement.

In second case, fault ride through (FRT) capability of microgrid has been introduced to see the impact of it on grid reliability. FRT helps to shorten long interruption duration by supplying power supply during power outage period to the interrupted nodes which helps to improve SAIDI and SAIFI.

In third case, the impact of multiple BESSs over grid reliability have been figured out. BESS installation in suitable BESS location increases the probability of microgrid support for interrupted nodes during fault condition. More microgrid possibility will support more interrupted nodes hence improve the grid performances. The impact of variable nominal fault rate and variable nominal fault duration have been also figured out in nominal microgrid condition. Microgrids have dominated interruption duration more effectively in variable fault duration compare to variable fault rate, important for improving grid performance. The enhancement of the overall grid reliability has been achieved through nominal microgrid condition

In fourth case, impact of maximum microgrid power supply condition over grid reliability has been studied well. Increased BESS size increases the customer handle capacity hence shorten interruption duration. Determined SAIDI values shows that maximum microgrid power supply condition improved the grid reliability.

5.1 Recommendation for future works

Several case study over the microgrid impact on grid reliability, recommendation for future work based on the present work could be as follows below:

This research only deals with major two grid reliability indices (SAIFI, SAIDI) to analysis the microgrid impact over MV/LV level distribution network. Other reliability indices could be taken in consideration as extended research of the present work.

Reliability determination tools or algorithms have been developed based on multiple assumptions, i.e. BESSs are able to carry the total load connected in BESSs nodes, microgrid equipped with autonomous switching facility to perform required operations. Developing algorithms including real time data instead of assumption could lead more weighty research.

Power quality, grid voltage label during the fault, network components loading analysis during fault condition and grid frequency deviation along with required grid protection system for the real network implementation could be possible area for future work.

Reliability including cost-benefit analysis during grid-connected mode and islanding operation in the grid is also an extended version of the thesis.

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7. APENDIX

7.1 SAIFI determination with and without fault ride through condition

```
%to read the data file
[~,~,CUST] = xlsread( gh, 'CONSUMER' );
[~,~,SW] = xlsread(gh, 'SW' );
[~,~,LINE] = xlsread( gh, 'LINE' );
[~,~,LINETYPE] = xlsread( gh, 'LINETYPE' );
[~,~,BACKUP] = xlsread( gh, 'SOURCENODES' );

% Removing header rows
CUST = CUST(2:end,:);
SW = SW(2:end,:);
LINE = LINE(2:end,:);
LINETYPE = LINETYPE(2:end,:);
BACKUP=BACKUP(2:end,:);
size(LINE);
% This is the list of all nodes in the network
node_names = unique( [LINE(:,[4 5]); SW(:,[2 3])] );
% This is the prototype G matrix, all zeros
G_matrics = zeros( length( node_names ) );
for line_ind = 1:size(LINE,1)
    % Reading begin and end node names from LINE row
    beg_node = LINE{line_ind,4};
    end_node = LINE{line_ind,5};

    % Determining the indices of said nodes in G
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );

    % Modifying G so that line is represented in G (line == 1, in G)
    G_matrics(beg_node_ind,end_node_ind)=1;
    G_matrics(end_node_ind,beg_node_ind)=1;
end

for sw_ind = 1:size(SW,1)

    % Reading node names and determining indices for switch nodes
    % in a similar manner as was did for lines
    beg_node = SW{sw_ind,2};
    end_node = SW{sw_ind,3};
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    % Modifying G so that the switch is represented in G
    % (Open Sw == 3, Closed Sw == 2, Breaker == 4)
    if SW{sw_ind,5}==1 %Closed Switch
        if SW{sw_ind,4}==0 %Breaker
            G_matrics(beg_node_ind,end_node_ind)=4;
            G_matrics(end_node_ind,beg_node_ind)=4;
        else
            G_matrics(beg_node_ind,end_node_ind)=2;
            G_matrics(end_node_ind,beg_node_ind)=2;
```

```
        end

      elseif SW{sw_ind,5}==0 %Open Switch
        G_matrics(beg_node_ind,end_node_ind)=3;
        G_matrics(end_node_ind,beg_node_ind)=3;
   end
end
SAIFI=SAIFI_f(G_matrics,CUST,node_names,LINE,LINETYPE);

function
[Calculate_SAIFI]=SAIFI_f(G_matrics,CUST,node_names,LINE,LINETYPE)
%% SAIFI Calculation
Calculate_SAIFI = 0;
% We modify G for the purposes for saifi calculation by removing
% open-switches and breakers from G
G_saifi = G_matrics;
G_saifi(G_saifi==4) = 0;
G_saifi(G_saifi==3) = 0;
G_saifi;
G_saifi = sparse( G_saifi );
TotalNCust = sum( cell2mat( CUST(:,2) ) );

for line = 1:size(LINE,1)
    % Reading line specific values for Line Type and Line length
    LineType = LINE{line,2};
    LineLength = LINE{line,3};
    % Reading Line begin node name
    LineBeginNodeName = LINE{line,4};
    % graphtraverse requires the node index of the begin node in
    % 'node_names'. This can be calculated with:
    [ ~, LineBeginNodeIndex] = max( ismember( node_names,
LineBeginNodeName ) );
    % Determining indices of the nodes which experience the fault...
    FaultNodeIndices = graphtraverse( G_saifi, LineBeginNodeIndex );
    %h = view(biograph(G_saifi));
    % ...and extarcting the faulty node names from
    FaultNodeNames = node_names( FaultNodeIndices );
    % Find the total number of affected customers by referencing the
    % customers which are part of the previously defined faulty node
set
    NFaultyCustomers = sum( cell2mat( CUST( ...
                     ismember(CUST(:,1),FaultNodeNames ),2)));
   %Find out the effective BESS nodes,so that ineffective BESS nodes
are not taken consideration.
     Min_SW_time=min(cell2mat(SW(:,4)));
     BESS_Nodes=cell(size(CUST(:,6)));
      for s=1:length(CUST(:,6))

          if cell2mat(CUST(s,6))>= Min_SW_time

           BESS_Nodes{s}=cell2mat(CUST(s,1));
          end

      end
   Efective_BESS_Nodes=BESS_Nodes(~cellfun('isempty',BESS_Nodes));

BESS_supported_Cust=sum(cell2mat(CUST(ismember(Efective_BESS_Nodes,Fau
ltNodeNames(:,1)),2)));
   %Remaining final intrrupted customer
```

```
   NFaultyCustomers =NFaultyCustomers- BESS_supported_Cust;
   % Line faut rate is read by reading the faultrate value from
   % LINETYPE from the row where Linetype mathces the type of this
   % specific line branch and multiplying it with line length.
   % NOTE: specific faultrates for linetypes are per km and line
length is
   % in m, hence the division with 1000
   LineFaultRate = LineLength / 1000 * ...
        LINETYPE{ ismember(LINETYPE(:,1),LineType),7};
   % Incrementing SAIFI:
   Calculate_SAIFI = Calculate_SAIFI + NFaultyCustomers/TotalNCust *
LineFaultRate;

end

end
```

7.2 SAIDI determination in nominal microgrid condition.

```
%CUST, SW, LINE, LINETYPE, and BACKUP represent the customer data
%array,switching data array,Line data array, Line characteristics data
%array, and Sourcenode respectively.
CUST = CUST(2:end,:);
SW = SW(2:end,:);
LINE = LINE(2:end,:);
LINETYPE = LINETYPE(2:end,:);
BACKUP=BACKUP(2:end,:)
size(LINE);
% This is the list of all nodes in the network
node_names = unique([LINE(:,[4 5]); SW(:,[2 3])]);

% This is the prototype G matrix, all zeros
G_matrics = zeros(length(node_names));
for line_ind = 1:size(LINE,1)
    % Reading begin and end node names from LINE row
    beg_node = LINE{line_ind,4};
    end_node = LINE{line_ind,5};
    % Determining the indices of said nodes in G
    beg_node_ind = ismember(node_names, beg_node );
    end_node_ind = ismember(node_names, end_node );
    % Modifying G so that line is represented in G (line == 1, in G)
    G_matrics(beg_node_ind,end_node_ind)=1;
    G_matrics(end_node_ind,beg_node_ind)=1;
end

 for sw_ind = 1:size(SW,1)
    % Reading node names and determining indices for switch nodes
    % in a similar manner as was did for lines
    beg_node = SW{sw_ind,2};
    end_node = SW{sw_ind,3};
    beg_node_ind = ismember(node_names, beg_node);
    end_node_ind = ismember(node_names, end_node);
    % Modifying G so that the switch is represented in G
    %  (Open Sw == 3, Closed Sw == 2, Breaker == 4)
    if SW{sw_ind,5}==1 %Closed Switch
        if SW{sw_ind,4}==0 %Breaker
            G_matrics(beg_node_ind,end_node_ind)=4;
            G_matrics(end_node_ind,beg_node_ind)=4;
```

```
        else
            G_matrics(beg_node_ind,end_node_ind)=2;
            G_matrics(end_node_ind,beg_node_ind)=2;
        end

    elseif SW{sw_ind,5}==0 %Open Switch
      G_matrics(beg_node_ind,end_node_ind)=3;
      G_matrics(end_node_ind,beg_node_ind)=3;
    end
 end

 G_SW = zeros( length(node_names));
 for line_ind = 1:size(LINE,1)
    % Reading begin and end node names from LINE row
    beg_node = LINE{line_ind,4};
    end_node = LINE{line_ind,5};
    % Determining the indices of said nodes in G
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    % Modifying G so that line is represented in G (line == 1, in G)
    G_SW(beg_node_ind,end_node_ind)=eps;
    G_SW(end_node_ind,beg_node_ind)=eps;
end

 for sw_ind = 1:size(SW,1)
    % Reading node names and determining indices for switch nodes
    % in a similar manner as was did for lines
    beg_node = SW{sw_ind,2};
    end_node = SW{sw_ind,3};
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    G_SW(beg_node_ind,end_node_ind)=(SW{sw_ind,4});
    G_SW(end_node_ind,beg_node_ind)=(SW{sw_ind,4});

 end
SAIDI=0;
 for line_S=  1:size(LINE,1)
%To show each index number during fault
Fault_line=line_S
%G_Islanding is modified version of G matrics for using in different
necessary condition
G_Matrics_SW=G_SW;

G_saidi_islanding=G_matrics;
%to find out parmanent faulted nodes, all swithches, breaker should be
kept open
G_saidi_islanding(G_saidi_islanding==4) = 0;
G_saidi_islanding(G_saidi_islanding==3) = 0;
G_saidi_islanding(G_saidi_islanding==2) = 0;
%Graph traveres required sparse matrics
G_saidi_islanding = sparse( G_saidi_islanding );
%h = view(biograph(G_saidi_islanding));
%Line_Type, Line_Length, and initial_fault_Node have been find out
from
%data XL
Line_Type = LINE{line_S,2};
Line_Length = LINE{line_S,3};
Initial_Fault_Node = LINE{line_S,4};
```

```
% Graphtraverse requires starting index to start depth-first search
algoritm
[ ~, Fault_Node_Index] = max( ismember( node_names, Initial_Fault_Node
) );
%Pr_Fault_Node_indexs are parmanent faulted nodes search by Depth-
first search algoritm.
Pr_Fault_Node_index = graphtraverse( G_saidi_islanding,
Fault_Node_Index);

Pr_Fault_Node_Name = node_names( Pr_Fault_Node_index);
%Pr_Faulted_Cust_number denotes the total number of customar that
sense the
%the parmanent fault
Pr_Faulted_Cust_initial=sum( cell2mat(CUST( ...
        ismember( CUST(:,1),Pr_Fault_Node_Name ),2)));
%Lamda and Fault_Repair_time is measured from different type of line
%for SAIDI calculation issue
Lamda = Line_Length / 1000 * ...
        LINETYPE{ ismember(LINETYPE(:,1),Line_Type),7};
Fault_Repair_Time= LINETYPE{ ismember(LINETYPE(:,1),Line_Type),8}/60;

Min_SW_time=min(cell2mat(SW(:,4)));
BESS_Nodes=cell(size(CUST(:,6)));
  for s=1:length(CUST(:,6))

    if cell2mat(CUST(s,6))>= Min_SW_time

       BESS_Nodes{s}=cell2mat(CUST(s,1));
    end

  end
Efective_BESS_Nodes=BESS_Nodes(~cellfun('isempty',BESS_Nodes));

for Bacup_ind=1:size(BACKUP,1)

       G_saidi_islanding=G_matrics;
       G_saidi_islanding(G_saidi_islanding==3)= 0;
       G_saidi_islanding = sparse( G_saidi_islanding );
       %h = view(biograph(G_saidi_islanding))
       [ ~, BackupNodeIndex] = max(ismember(
node_names,BACKUP(Bacup_ind,1)));
       Node_In_Backup_path =
graphtraverse(G_saidi_islanding,BackupNodeIndex);
       NodeName_In_Backup_path=node_names( Node_In_Backup_path);

check_fault_zone=ismember(NodeName_In_Backup_path(:,1),Initial_Fault_N
ode);
       %Determine the fault zone hence the sourcenode which is
responsible
       %for backup connection
       if max(check_fault_zone)==1

Check_BESS_Availibility=ismember(Efective_BESS_Nodes,NodeName_In_Backu
p_path(:,1));

BESS_Nodes_In_Backup_path=Efective_BESS_Nodes(Check_BESS_Availibility(
:,1));
           Switch=ismember(SW(:,[2 3]),Pr_Fault_Node_Name);
```

```
            Swithch_involved=[SW(Switch(:,1),[2 3]);SW(Switch(:,2),[2
3])];
             for i=1:size(Swithch_involved)
                   Beg_required_sw=ismember(node_names,
Swithch_involved(i,1));
                   End_required_Sw = ismember(node_names,
Swithch_involved(i,2));

G_saidi_islanding(Beg_required_sw,End_required_Sw)=0;

G_saidi_islanding(End_required_Sw,Beg_required_sw)=0;
             end
            G_saidi_islanding = sparse( G_saidi_islanding );
            %h = view(biograph(G_saidi_islanding))
            Short_time_faulted_node =
graphtraverse(G_saidi_islanding,BackupNodeIndex);
            Short_time_faulted_node_name=
node_names(Short_time_faulted_node);

Reamaining_open_node=setxor(NodeName_In_Backup_path,Short_time_faulted
_node_name);
            %Remaining_open_node represents the rest of the node which
are not possible to rennect from sourcenode
            Open_node=setxor( Reamaining_open_node,Pr_Fault_Node_Name);
            %Open_node represents the nodes which are traeted as
parmament fault

BESS_In_OpenNode=ismember(Open_node,BESS_Nodes_In_Backup_path);
            Open_node_withoutBESS=Open_node(BESS_In_OpenNode);
            Check_short_Sw_Time=ismember(SW(:, [2 3]),
Short_time_faulted_node_name);

Total_Path_Cust=sum(cell2mat(CUST(ismember(CUST(:,1),NodeName_In_Backu
p_path),2)));

Short_sw_time=min(cell2mat([SW(Check_short_Sw_Time(:,1),4);SW(Check_sh
ort_Sw_Time(:,2),4)]))/3600;
            Check_long_Sw_Time=ismember(SW(:, [2 3]),
Short_time_faulted_node_name);
            %Finiding the longest switching perio

Long_sw_time=max(cell2mat([SW(Check_long_Sw_Time(:,1),4);SW(Check_long
_Sw_Time(:,2),4)]))/3600;
            %Finid out is there any BESS available in parmanent faulted
nodes hence update the parmanent faulted customer

             if isempty(Open_node)==0
                Cust_treat_PRF=cell(length(BACKUP),1);
                Manual_SW_T=cell(length(BACKUP),1);
                %Try to reach parmanent fault nodes fron any possible
sourcenodes.
                for B=1:size(BACKUP,1)
                    Gmatrics_w=G_SW ;
                    Switch=ismember(SW(:,[2 3]),Pr_Fault_Node_Name);
                    Swithch_involved=[SW(Switch(:,1),[2
3]);SW(Switch(:,2),[2 3])];
                  for i=1:size(Swithch_involved)
                      Beg_required_sw=ismember(node_names,
Swithch_involved(i,1));
```

```
                    End_required_Sw = ismember(node_names,
Swithch_involved(i,2));
                    Gmatrics_w(Beg_required_sw,End_required_Sw)=0;
                    Gmatrics_w(End_required_Sw,Beg_required_sw)=0;
                end
                  Gmatrics_w= sparse(Gmatrics_w);
                  %h = view(biograph(Gmatrics_w))
                  [ ~, BackupNodeIndex]
=max(ismember(node_names,BACKUP(B,1)));
                  [ ~,
TargetIndex]=max(ismember(node_names,Open_node(1,1)));
                  [dist, path, pred]=
graphshortestpath(Gmatrics_w,BackupNodeIndex,TargetIndex);
                  distf=dist/3600;
                  %In case of possible connection through sourcenode
                     if isinf(distf)==0
                        Manual_SW_T{B}=fix(distf);
                     end
                  if distf==inf
                    %In case of zero possibility connection through
                    %sourcenode,chk_bess represent the result of BESS
availabilty in nodes
                    chk_bess=ismember(
BESS_Nodes_In_Backup_path,Open_node);

                        if max(chk_bess)==1
                           Pr_Faulted_Custi =Pr_Faulted_Cust_initial;
                        else
                           Pr_Faulted_Custi
=(Pr_Faulted_Cust_initial+sum(cell2mat(CUST(ismember(CUST(:,1),Open_no
de),2))));
                        end
                  else
                      Pr_Faulted_Custi =Pr_Faulted_Cust_initial ;
                  end
             Cust_treat_PRF{B}=Pr_Faulted_Custi;
              end
             %Manual_SW_Tf denotes the minimum switching duration
among all N/O switches
             Manual_SW_Tf=min(cell2mat(Manual_SW_T(:,1)));
                if isempty(Manual_SW_Tf)==1
                 Manual_SW_Tf=Fault_Repair_Time;
               end
            Pr_Faulted_Cust= min(cell2mat(Cust_treat_PRF(:,1)));
           else
              Manual_SW_Tf=Long_sw_time;
              Pr_Faulted_Cust =Pr_Faulted_Cust_initial;
           end
          %Update the short time faulted customer and longtime
customer
          %based on updated parmanent faulted customer
          if max(Check_BESS_Availibility)==1

BESS_Supported_customer=cell(size(BESS_Nodes_In_Backup_path(:,1)));
             for b=1:size(BESS_Nodes_In_Backup_path(:,1))
               [ ~, BESSIndex]=max(
ismember(node_names,BESS_Nodes_In_Backup_path(b,1)));
               %BESSsuportedNode and BESSsuportedNode_name denotes
BESS
               %connected node and node name respectively
```

```
BESSsuportedNode=graphtraverse(G_saidi_islanding,BESSIndex);
                BESSsuportedNode_name=node_names(BESSsuportedNode);
                %To check BESS option in parmanent foulted nodes and
short
                %time faulted nodes

Check_BESSIN_FaultedBrance=ismember(Pr_Fault_Node_Name,BESS_Nodes_In_B
ackup_path(b,1));
                Check_BESS_In_Shortpath=ismember(
Short_time_faulted_node_name,BESS_Nodes_In_Backup_path(b,1));
                  if max(Check_BESSIN_FaultedBrance)==1
                     BESS_Suported_Cust=0 ;
                  elseif max(Check_BESS_In_Shortpath)==1
                     BESS_Suported_Cust=0;
                  else

BESS_Suported_Cust=sum(cell2mat(CUST(ismember(CUST(:,1),BESSsuportedNo
de_name),2)));
                  end
                %BESS_Supported_customer denotes the customer are
backuped by BESS
                BESS_Supported_customer{b} =BESS_Suported_Cust;
             end

Total_BESS_Supported_customer=max(cell2mat(BESS_Supported_customer));

shortime_customer=sum(cell2mat(CUST(ismember(CUST(:,1),Short_time_faul
ted_node_name),2)))+Total_BESS_Supported_customer;
             longtime_customer= Total_Path_Cust-
(shortime_customer+Pr_Faulted_Cust);
           else

shortime_customer=sum(cell2mat(CUST(ismember(CUST(:,1),Short_time_faul
ted_node_name),2)));
           longtime_customer= Total_Path_Cust-
(shortime_customer+Pr_Faulted_Cust);
           end

      end

end
Total_Path_Cust;
Pr_Faulted_Cust;
shortime_customer;
longtime_customer;
Manual_SW_Tf;
Total_Cust_Number = sum( cell2mat( CUST(:,2)));
%Total_Cust_Number represent the total customer connected the system
 if longtime_customer>=0
   if isempty(Manual_SW_Tf)==0

SAIDI=SAIDI+((Lamda.*Pr_Faulted_Cust.*Fault_Repair_Time)+(Lamda.*longt
ime_customer.*Manual_SW_Tf)+(Lamda.*
shortime_customer.*Short_sw_time))/Total_Cust_Number;
     SAIDI_Final=SAIDI ;
  end
 end
 end
```

```
SAIDI_Final;
```

7.3 SAIDI determination in maximum microgrid supply condition.

```
%CUST, SW, LINE, LINETYPE, and BACKUP represent the customer data
%array,switching data array,Line data array, Line characteristics data
%array, and Sourcenode respectively.
CUST = CUST(2:end,:);
SW = SW(2:end,:);
LINE = LINE(2:end,:);
LINETYPE = LINETYPE(2:end,:);
BACKUP=BACKUP(2:end,:);
size(LINE);
% This is the list of all nodes in the network
node_names = unique( [LINE(:,[4 5]); SW(:,[2 3])] );

% This is the prototype G matrix, all zeros
G_matrics = zeros( length( node_names ) );
for line_ind = 1:size(LINE,1)
    % Reading begin and end node names from LINE row
    beg_node = LINE{line_ind,4};
    end_node = LINE{line_ind,5};
    % Determining the indices of said nodes in G
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    % Modifying G so that line is represented in G (line == 1, in G)
    G_matrics(beg_node_ind,end_node_ind)=1;
    G_matrics(end_node_ind,beg_node_ind)=1;
end

 for sw_ind = 1:size(SW,1)
    % Reading node names and determining indices for switch nodes
    % in a similar manner as was did for lines
    beg_node = SW{sw_ind,2};
    end_node = SW{sw_ind,3};
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    % Modifying G so that the switch is represented in G
    % (Open Sw == 3, Closed Sw == 2, Breaker == 4)
    if SW{sw_ind,5}==1 %Closed Switch
        if SW{sw_ind,4}==0 %Breaker
            G_matrics(beg_node_ind,end_node_ind)=4;
            G_matrics(end_node_ind,beg_node_ind)=4;
        else
            G_matrics(beg_node_ind,end_node_ind)=2;
            G_matrics(end_node_ind,beg_node_ind)=2;
        end

    elseif SW{sw_ind,5}==0 %Open Switch
      G_matrics(beg_node_ind,end_node_ind)=3;
      G_matrics(end_node_ind,beg_node_ind)=3;
    end
 end

 G_SW = zeros( length(node_names));
 for line_ind = 1:size(LINE,1)
```

```
    % Reading begin and end node names from LINE row
    beg_node = LINE{line_ind,4};
    end_node = LINE{line_ind,5};
    % Determining the indices of said nodes in G
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    % Modifying G so that line is represented in G (line == 1, in G)
    G_SW(beg_node_ind,end_node_ind)=eps;
    G_SW(end_node_ind,beg_node_ind)=eps;
end

 for sw_ind = 1:size(SW,1)
    % Reading node names and determining indices for switch nodes
    % in a similar manner as was did for lines
    beg_node = SW{sw_ind,2};
    end_node = SW{sw_ind,3};
    beg_node_ind = ismember( node_names, beg_node );
    end_node_ind = ismember( node_names, end_node );
    G_SW(beg_node_ind,end_node_ind)=(SW{sw_ind,4});
    G_SW(end_node_ind,beg_node_ind)=(SW{sw_ind,4});

 end

SAIDI=0;
 for line_S=  1:size(LINE,1)
%To show each index number during fault
Fault_line=line_S
%G_Islanding is modified version of G matrics for using in different
necessary condition
G_Matrics_SW=G_SW;
G_saidi_islanding=G_matrics;
%to find out parmanent faulted nodes, all swithches, breaker should be
kept open
G_saidi_islanding(G_saidi_islanding==4) = 0;
G_saidi_islanding(G_saidi_islanding==3) = 0;
G_saidi_islanding(G_saidi_islanding==2) = 0;
%Graph traveres required sparse matrics
G_saidi_islanding = sparse( G_saidi_islanding );
%h = view(biograph(G_matrics)
%Line_Type, Line_Length, and initial_fault_Node have been find out
from
%data XL
Line_Type = LINE{line_S,2};
Line_Length = LINE{line_S,3};
Initial_Fault_Node = LINE{line_S,4};
% Graphtraverse requires starting index to start depth-first search
algoritm
[ ~, Fault_Node_Index] = max( ismember( node_names, Initial_Fault_Node
) );
%Pr_Fault_Node_Name shows the parmanent faulted nodes search by Depth-
first search algoritm.
Pr_Fault_Node_index = graphtraverse( G_saidi_islanding,
Fault_Node_Index);
Pr_Fault_Node_Name = node_names( Pr_Fault_Node_index);
%Pr_Faulted_Cust_initial denotes the total number of customar that
sense the
%the parmanent fault
Pr_Faulted_Cust_initial=sum( cell2mat(CUST( ...
        ismember( CUST(:,1),Pr_Fault_Node_Name ),2)));
```

```
%Lamda and Fault_Repair_time is measured from different type of line
for SAIDI calculation issue
Lamda = Line_Length / 1000 * ...
        LINETYPE{ ismember(LINETYPE(:,1),Line_Type),7};
Fault_Repair_Time= LINETYPE{ ismember(LINETYPE(:,1),Line_Type),8}/60;

%Find out the effective BESS nodes,so that ineffective BESS nodes are
not taken consideration.
 Min_SW_time=min(cell2mat(SW(:,4)));
 BESS_Nodes=cell(size(CUST(:,6)));
 for s=1:length(CUST(:,6))
    if cell2mat(CUST(s,6))>= Min_SW_time
       BESS_Nodes{s}=cell2mat(CUST(s,1));
    end
 end
Efective_BESS_Nodes=BESS_Nodes(~cellfun('isempty',BESS_Nodes));

for Bacup_ind=1:size(BACKUP,1)

         G_saidi_islanding=G_matrics;
         %keep the open switch open
         G_saidi_islanding(G_saidi_islanding==3)= 0;
         G_saidi_islanding = sparse( G_saidi_islanding );
         [ ~, BackupNodeIndex] = max( ismember(
node_names,BACKUP(Bacup_ind,1)));
         % Finding nodes that are connectd to the source nodes
         Node_In_Backup_path =
graphtraverse(G_saidi_islanding,BackupNodeIndex);
         NodeName_In_Backup_path=node_names( Node_In_Backup_path);
         %Determine the fault zone hence the sourcenode which is
responsible for backup connection

check_fault_zone=ismember(NodeName_In_Backup_path(:,1),Initial_Fault_N
ode);

       if max(check_fault_zone)==1
           %Checking the BESS availibility in backup source connected
path

Check_BESS_Availibility=ismember(Efective_BESS_Nodes,NodeName_In_Backu
p_path(:,1));

BESS_Nodes_In_Backup_path=Efective_BESS_Nodes(Check_BESS_Availibility(
:,1));
           Switch=ismember(SW(:,[2 3]),Pr_Fault_Node_Name);
           %Findout the switches that are connected with parmanent
faulted
           %nodes
           Swithch_involved=[SW(Switch(:,2),[2 3]);SW(Switch(:,1),[2
3])];
           %Temporary faulted nodes will be founed after faulted brach
isolation from
           %the network
           G_saidi_islanding=G_matrics;
           G_saidi_islanding(G_saidi_islanding==3)=0;

            for i=1:size(Swithch_involved)
                %Modufy the G matrix for parmanent faulted zone
isolation
```

```
                  Beg_required_sw=ismember(node_names,
Swithch_involved(i,1));
                  End_required_Sw = ismember(node_names,
Swithch_involved(i,2));

G_saidi_islanding(Beg_required_sw,End_required_Sw)=0;

G_saidi_islanding(End_required_Sw,Beg_required_sw)=0;
            end

           G_saidi_islanding;
           G_saidi_islanding = sparse( G_saidi_islanding );

           %h = view(biograph(G_saidi_islanding));
           %Finding the momentary intrrupted nodes
           Short_time_faulted_node =
graphtraverse(G_saidi_islanding,BackupNodeIndex);
           Short_time_faulted_node_name=
node_names(Short_time_faulted_node);
           %Remaining_open_node represents the rest of the node which
           %are not possible to supply from sourcenode

Reamaining_open_node=setxor(NodeName_In_Backup_path,Short_time_faulted
_node_name);
           %Open_node represents the nodes which are traeted as
           %parmament fault
           Open_node=setxor( Reamaining_open_node,Pr_Fault_Node_Name);
           %Check, any load connected to the nodes which are treated
as
           %parmanent faulted nodes
           Loaded_open_node=CUST(ismember(CUST(:,1),Open_node),1);
           Check_short_Sw_Time=ismember(SW(:, [2 3]),
Short_time_faulted_node_name);
           %Count the total customer in faulted feeder

Total_Path_Cust=sum(cell2mat(CUST(ismember(CUST(:,1),NodeName_In_Backu
p_path),2)));
           %Finding short intrruption duration and long intrruption
           %duration

Short_sw_time=min(cell2mat([SW(Check_short_Sw_Time(:,1),4);SW(Check_sh
ort_Sw_Time(:,2),4)]))/3600;
Check_long_Sw_Time=ismember(SW(:, [2 3]),
Short_time_faulted_node_name);

Long_sw_time=max(cell2mat([SW(Check_long_Sw_Time(:,1),4);SW(Check_long
_Sw_Time(:,2),4)]))/3600;
           %To check out is there any BESS available in parmanent
faulted
           %nodes and hence update the parmanent faulted customer
           if isempty(Open_node)==0
             Cust_treat_PRF=cell(length(BACKUP),1);
             Manual_SW_T=cell(length(BACKUP),1);
             %Try to reach parmanent nodes fron any possible
sourcenodes.
             for B=1:size(BACKUP,1)
                 Gmatrics_w=G_SW ;
                 Switch=ismember(SW(:,[2 3]),Pr_Fault_Node_Name);
```

```
                    Swithch_involved=[SW(Switch(:,1),[2 
3]);SW(Switch(:,2),[2 3])];
                    for i=1:size(Swithch_involved)
                      Beg_required_sw=ismember(node_names, 
Swithch_involved(i,1));
                      End_required_Sw = ismember(node_names, 
Swithch_involved(i,2));
                      Gmatrics_w(Beg_required_sw,End_required_Sw)=0;
                      Gmatrics_w(End_required_Sw,Beg_required_sw)=0;
                    end
                   Gmatrics_w= sparse(Gmatrics_w);
                   %h = view(biograph(Gmatrics_w))
                   [ ~, BackupNodeIndex] 
=max(ismember(node_names,BACKUP(B,1)));
                   [ ~, 
TargetIndex]=max(ismember(node_names,Open_node(1,1)));
                   %Finding the total switching duration to reach the 
target
                   %node from sorucenode
                   [dist, path, pred]= 
graphshortestpath(Gmatrics_w,BackupNodeIndex,TargetIndex);
                   distf=dist/3600;

                    %In case of possible connection through sourcenode
                      if isinf(distf)==0
                         Manual_SW_T{B}=fix(distf);
                      end
                    if distf==inf
                      %In case of zero possibility connection through
                      %sourcenode,chk_bess represent the result of BESS 
availabilty in nodes
                      cHk_Loaded_open_node=ismember(CUST(:,1),Open_node);
                      if max(cHk_Loaded_open_node)==1
                        chk_bess=ismember(
BESS_Nodes_In_Backup_path,Loaded_open_node);
                        BESS_Node=BESS_Nodes_In_Backup_path(chk_bess);

BESS_Capacity_InfaultyZone=sum(cell2mat(CUST(ismember(CUST(:,1),BESS_N
ode),5)));

Connected_load_InfaultyZone=cell2mat((CUST(ismember(CUST(:,1),Loaded_o
pen_node),3)))*Fault_Repair_Time;
                        %Total_load_InfaultyZone denotes total load that 
is out of power supply

Total_load_InfaultyZone=sum(cell2mat(CUST(ismember(CUST(:,1),Loaded_op
en_node),3)))*Fault_Repair_Time;

Connected_Cust_InfaultyZone=CUST(ismember(CUST(:,1),Loaded_open_node),
2);
                        Cust=0;
                         if 
BESS_Capacity_InfaultyZone>=Connected_load_InfaultyZone(1,1)
                              for k=1:size(Connected_load_InfaultyZone,1)

c=Cust+cell2mat(Connected_Cust_InfaultyZone(k,1));
                                Cust=c;
                                %Pr_Faulted_Custi denotes the final 
parmanent faulted customer
```

```
                          Pr_Faulted_Custi
=Pr_Faulted_Cust_initial+(sum(cell2mat(CUST(ismember(CUST(:,1),Loaded_
open_node),2)))-Cust);
                           if
(BESS_Capacity_InfaultyZone==Total_load_InfaultyZone)
                              break
                           end
                        end
                      else
                       Pr_Faulted_Custi
=(Pr_Faulted_Cust_initial+sum(cell2mat(CUST(ismember(CUST(:,1),Open_no
de),2))));
                      end
                   else
                     Pr_Faulted_Custi =Pr_Faulted_Cust_initial ;
                   end

                 else
                 Pr_Faulted_Custi =Pr_Faulted_Cust_initial ;
                end
                    %Cust_treat_PRF represent the customer those are
treated as parmanent faulted customer
                    Cust_treat_PRF{B}=Pr_Faulted_Custi;
             end
                   %Manual_SW_Tf denotes the minimum switching
duration
                   %among all N/O switches
                   Manual_SW_Tf=min(cell2mat(Manual_SW_T(:,1)));
                   if isempty(Manual_SW_Tf)==1
                    Manual_SW_Tf=Fault_Repair_Time;
                   end
                   Pr_Faulted_Cust=
min(cell2mat(Cust_treat_PRF(:,1)));
           else
               Manual_SW_Tf=Long_sw_time;
               Pr_Faulted_Cust =Pr_Faulted_Cust_initial;
           end
           %Update the short time faulted customer and longtime
customer
           %based on updated parmanent faulted customer
           if max(Check_BESS_Availibility)==1

BESS_Supported_customer=cell(size(BESS_Nodes_In_Backup_path(:,1)));
               for b=1:size(BESS_Nodes_In_Backup_path(:,1))

check_BESSIN_FaultedBrance=ismember(Pr_Fault_Node_Name,BESS_Nodes_In_B
ackup_path(b,1));
                 Check_BESS_In_Shortpath=ismember(
Short_time_faulted_node_name,BESS_Nodes_In_Backup_path(b,1));
                   if max(check_BESSIN_FaultedBrance)==1
                      BESS_Suported_Cust=0 ;
                   elseif max(Check_BESS_In_Shortpath)==1
                      BESS_Suported_Cust=0;
                   else
                   cHk_Loaded_open_node=ismember(CUST(:,1),Open_node);
                      if max(cHk_Loaded_open_node)==1
                        chk_bess=ismember(
BESS_Nodes_In_Backup_path,Loaded_open_node);
                        BESS_Node=BESS_Nodes_In_Backup_path(chk_bess);
```

```
BESS_Capacity_InfaultyZone=sum(cell2mat(CUST(ismember(CUST(:,1),Loaded
_open_node),5)));

Connected_load_InfaultyZone=cell2mat((CUST(ismember(CUST(:,1),Loaded_o
pen_node),3)))*Manual_SW_Tf;

Total_load_InfaultyZone=sum(cell2mat(CUST(ismember(CUST(:,1),Loaded_op
en_node),3)))*Manual_SW_Tf;

Connected_Cust_InfaultyZone=CUST(ismember(CUST(:,1),Loaded_open_node),
2);
                        Cust=0;
                         if
BESS_Capacity_InfaultyZone>=Connected_load_InfaultyZone(1,1)
                            for
k=1:size(Connected_load_InfaultyZone,1)

c=Cust+cell2mat(Connected_Cust_InfaultyZone(k,1));
                             Cust=c;
                             BESS_Suported_Cust =Cust;
                               if
(BESS_Capacity_InfaultyZone==Total_load_InfaultyZone)
                                 break
                               end
                            end
                         else
                            BESS_Suported_Cust =0;
                         end
                       else
                       BESS_Suported_Cust =0
                       end

                   end

                    BESS_Supported_customer{b} =BESS_Suported_Cust;
               end

Total_BESS_Supported_customer=max(cell2mat(BESS_Supported_customer));

shortime_customer=sum(cell2mat(CUST(ismember(CUST(:,1),Short_time_faul
ted_node_name),2)))+Total_BESS_Supported_customer;
           longtime_customer= Total_Path_Cust-
(shortime_customer+Pr_Faulted_Cust);
           else

shortime_customer=sum(cell2mat(CUST(ismember(CUST(:,1),Short_time_faul
ted_node_name),2)));
           longtime_customer= Total_Path_Cust-
(shortime_customer+Pr_Faulted_Cust);
           end
      end
end
Total_Path_Cust;
Pr_Faulted_Cust;
shortime_customer;
longtime_customer;
Manual_SW_Tf;
Total_Cust_Number = sum( cell2mat( CUST(:,2)));
```

```
%Total_Cust_Number represent the total customer connected the system
     if longtime_customer>=0
        if isempty(Manual_SW_Tf)==0

SAIDI=SAIDI+((Lamda.*Pr_Faulted_Cust.*Fault_Repair_Time)+(Lamda.*longt
ime_customer.*Manual_SW_Tf)+(Lamda.*
shortime_customer.*Short_sw_time))/Total_Cust_Number;
           SAIDI_Final=SAIDI ;
        end
     end
 end
 SAIDI_Final;
```